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ROCKET ENGINE POWER BALANCE AND OPTIMIZATION CODE USER'S MANUAL

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FOREWORD

A copy of the Rocketdyne Engine Balance and Optimization Program was provided to NASA-MSFC in March, 1982. This user's manual was prepared under contract NAS8-34642 to provide documentation for the program. The NASA contracting Officer's Representatives were Jeff Tuttle and Bob Richmond. Rocketdyne personnel participating in the documentation included Jim Glass, Duc Nguyen, and Bill Sprague.

ABSTRACT

The Rocketdyne Engine Balance and Optimization Program is designed to analyze bipropellant pump-fed liquid rocket engines. Cycle options include staged combustion, expander, and gas generator cycles. Propellant combinations include O_2/H_2, O_2/CH_4, O_2/C_3H_8, O_2/RP-1, and NTO/MMH. An optimizing routine is incorporated to vary turbopump operating parameters to maximize chamber pressure, minimize pump discharge pressure, or minimize turbine flowrates.

This user's manual provides a program description, user instructions, and definition of input/output variables.

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INTRODUCTION & SUMMARY

The Rocketdyne Engine Balance and Optimization Program is designed to perform flow and power balances, calculate engine performance, and optimize operating parameters for a pump-fed, bi-propellant, liquid rocket engine. The program models staged combustion, expander, and gas generator cycles and is structured to allow new schematic and propellant options to be easily added. Propellant combinations currently incorporated include: O_2/H_2, O_2/CH_4, O_2/RP-1, O_2/C_3H_8 (NBP), O_2/C_3H_8 (subcooled), and NTO/MMH.

Previous versions of this program have been run on IBM, Univac, and CDC computers and care has been taken to avoid utilizing language features unique to a particular computer system. This manual describes implementation on a Univac 1100-83.

ANALYTICAL APPROACH

Analysis of a liquid rocket engine requires calculation of delivered specific impulse, balancing of flowrates and pressures, matching pump and turbine horsepowers, and may include optimization of various component operating conditions. Key parameters defining a rocket engine include the following:

Thrust level, F
Chamber pressure, P_c
Area ratio, ε (exit area/throat area)
Nozzle percent length, δ (nozzle length/length of 15° cone with same area ratio)
Propellant combination
Mixture ratio (oxidizer/fuel)
Cycle/schematic

Engine Performance

Engine performance is calculated based on the simplified JANNAF methodology. The theoretical specific impulse is based on a one-dimensional isentropic equilibrium expansion and is a function of chamber pressure, mixture ratio, area ratio, and propellant enthalpy entering the chamber. The theoretical value is then reduced by the various losses occurring in the combustor and nozzle. If there is more than one flow stream, e.g., dump coolant or gas generator cycle turbine exhaust, the specific impulse is calculated for each stream and mass-averaged. The performance losses are described below.

Energy Release Loss (C*loss). The energy release loss includes those factors which prevei complete combustion and chemical equilibrium, primarily incomplete mixing and vaporization. There are models for analytically determining these losses, based on chamber and injector geometries and propellant properties, but empirical values are generally used.

Reaction Kinetic Loss. As the combustion products expand in the nozzle, the chemical reactions do not occur fast enough to maintain equilibrium as the pressure and temperature are reduced. Some of the energy that is released as dissociated species recombine is therefore unavailable. The kinetic loss is a function of thrust, chamber pressure, area ratio, and mixture ratio.

Divergence Loss. The divergence loss accounts for non-axial flow at the nozzle exit plane and is a function of area ratio and nozzle percent length.

Boundary Layer Loss. The boundary layer loss includes both friction losses and heat lost to the nozzle walls through the boundary layer. It depends on thrust, chamber pressure, area ratio, and nozzle percent length. The type of nozzle cooling also affects the boundary layer loss, since the loss decreases with increasing wall temperature.

Engine Balance

An engine balance is performed to match pressures, flowrates, and power levels throughout the engine. It is normally an iterative process since many calculated parameters are interdependent. A typical staged combustion cycle is shown in Figure 1 and the balance procedure is outlined in Figure 2 .

The balance begins with initial guesses on required parameters, primarily turbine pressure ratios and fuel enthalpy levels entering the preburners and combustor. With the assumed combustor enthalpy, the specific impulse and propellant flowrates can be calculated. The pressure schedule is next determined by working backwards from the chamber pressure to the pump discharge pressures. Coolant heat loads and pressure drops are determined from curve-fits, tabular data, or scaling equations. With flowrates and pump pressure rises determined, the pump power requirements are calculated along with the turbine flowrates required to provide the power. The specific impulse is then recalculated with updated enthalpies and compared with the previous value. Turbine pressure ratios may be varied to match available and required flowrates.

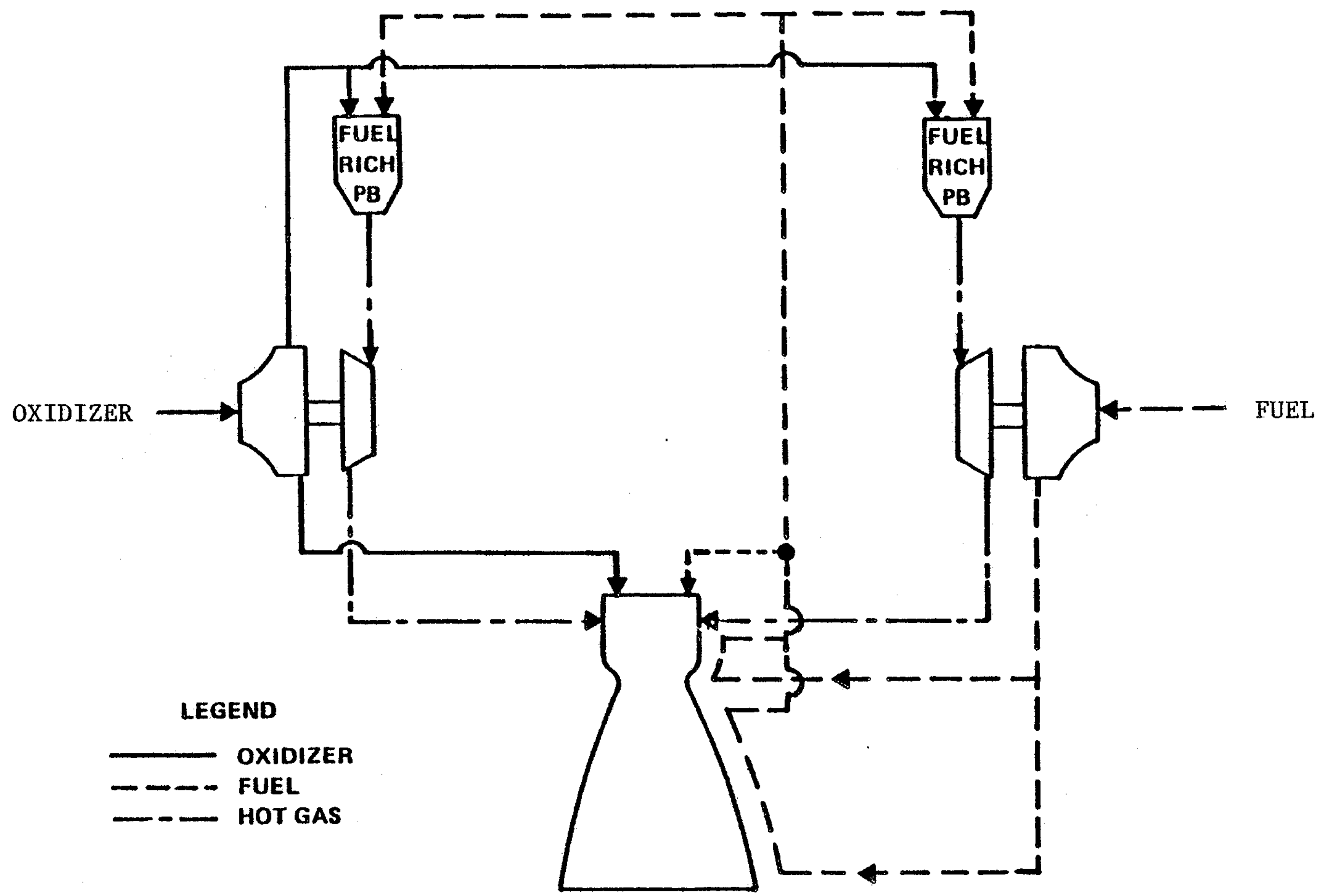

FIGURE 1. STAGED COMBUSTION CYCLE SCHEMATIC

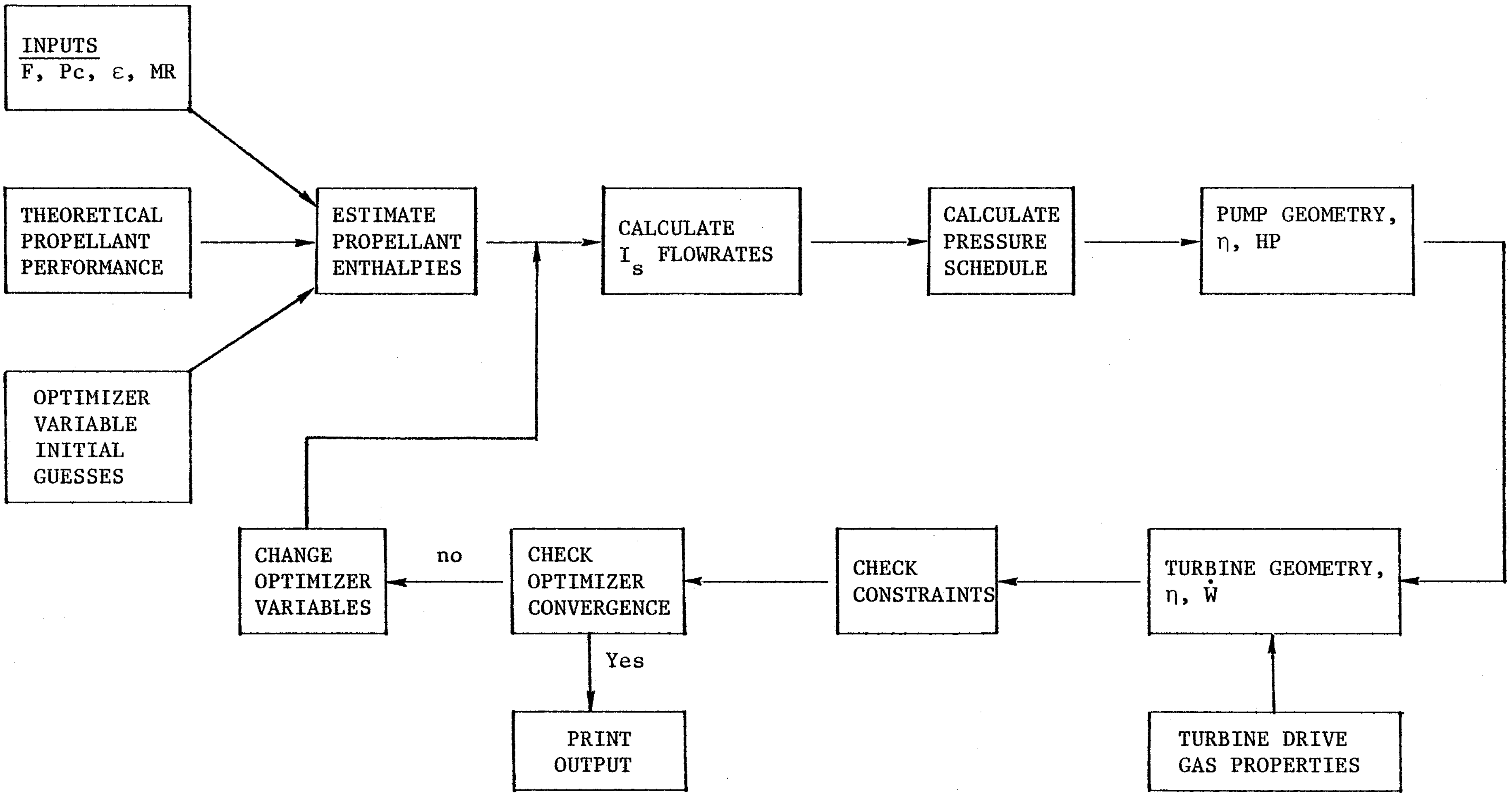

FIGURE 2. ENGINE BALANCE METHODOLOGY

Optimization

The balance program incorporates an optimization routine to vary selected independent variables to arrive at an optimum engine design. The optimizer can be used to maximize chamber pressure, minimize fuel pump discharge pressure, or minimize turbine flowrates. The first two options are typically used with staged combustion and expander cycles and the latter with gas generator cycles. Parameters varied by the optimizer include turbopump speeds, turbine admission fractions, and fuel turbine pressure ratio. The ratio of combustor coolant flow to total fuel flow is also varied but has no effect with the heat transfer data currently in the program.

The optimizer requires initial guesses for the independent variables which do not result in any constraint violations. The Box Complex optimization method is then used to vary the independent variables until an optimum is reached. Each point selected by the optimizer is checked, and rejected if a constraint violation occurs.

Constraints applied include both explicit (user-supplied upper and lower limits on the independent variables) and implicit (user-supplied or program limits on calculated variables, such as pump tip speed).

Two optimization steps are used if the chamber pressure maximization or pump discharge pressure minimization options are selected. The first step minimizes turbine flow until the required flow is less than the available flow. The second step then proceeds with the user-selected optimization. This two-step process makes the selection of initial guesses much less critical.

PROGRAM DESCRIPTION

The balance program is comprised of a main program and 30 subprograms. The main program (AMAIN) controls the input and output and calls the balance routine (MAIND) which contains the bulk of the engine balance logic and calls other routines for component designs and characteristics. Functions of the various routines are shown in Table 1 . Program features, characteristics, and options are summarized below:

- Program input - Three files are read containing the required data for program operation. The first contains theoretical specific impulse and c-star data. The second is optional and contains kinetic efficiency tables; a constant value can be input in lieu of these tables. The third file contains the user-supplied data describing the case to be run. Default values are incorporated in the program so only those values differing from the default must be input.

- Program output - A formatted output is provided which includes a description of the options selected and the calculated engine parameters of most interest. In addition, the common block containing input and output variables is printed.

- Propellant combinations - Theoretical performance data files are available and propellant property data are built-in for the following propellant combinations, although there are some gaps in the thrust chamber cooling and turbine drive gas data.

O_2/H_2	O_2/C_3H_8 (NBP)
O_2/CH_4	O_2/C_3C_8 (subcooled)
O_2/RP-1	NTO/MMH

TABLE 1. BALANCE PROGRAM SUBROUTINE FUNCTIONS

<u>INPUT/OUTPUT</u>

BDATA
DATARD
PRINT
DUMPER
AMAIN

<u>TABLE LOOKUP</u>

GIP4
DBLGIP
CURVES
INTRP

<u>PERFORMANCE</u>

IMPULS
CSIS
CSTAR1
CSUBF
KINEFF

<u>TURBOMACHINERY</u>

TRBN1D
PUMPD
EFF
EFFP
PMPCNV
PROCES

<u>PRESSURE SCHEDULE</u>

DELTAD
REGEN

<u>OPTIMIZATION</u>

OPT
EXPL
IMPL

<u>ITERATION</u>

EST

<u>PROPELLANT PROPERTIES</u>

PRPRP
TEMP

<u>ENGINE BALANCE</u>

MAIND

<u>MISC</u>

EHCABC
ZERO

- Engine cycle options - The following cycle options are currently available:

Staged combustion	- fuel rich preburners
	mixed preburners
	oxidizer-rich preburners
Expander	- parallel turbines
	series turbines
Gas generator	- parallel turbines
	series turbines

- Pumps - Centrifugal pumps with one or more stages are modeled, providing performance estimates and sufficient geometry to allow calculation of operating parameters subject to user-supplied limits. Stage specific speeds are limited to approximately 400 - 2000.

- Turbines - Turbines are also modeled to provide performance and geometry data. The following turbine types can be selected:

  1 - row impulse
  2 - row impulse
  1 - stage 50% reaction
  2 - stage impulse
  2 - stage 50% reaction

- Boost pumps - Boost pumps (also called low-pressure pumps) are no longer included in the program because their effect on the balance is relatively minimal compared to the added complexity and increased run time that result if they are included. The need for a boost pump is determined by comparing the available and required NPSH of the main pumps and minimum boost pump pressure rises are calculated and printed. An option is provided to constrain the main pumps to operate with the available NPSH, in which case boost pumps are not needed.

- Injectors, valves, and ducts - Pressure drops across injectors, valves, and ducts are calculated with user-supplied loss factors.

- Thrust chamber cooling - A limited amount of data are included in the program to provide combustion chamber and nozzle coolant heat loads and pressure drops. These values can also be input by the user.

USER INSTRUCTIONS

This section describes the use of the program, including the mechanics of setting up JCL to compile, map, and run the program, and data input to select the desired configuration and options.

JOB CONTROL LANGUAGE

The JCL required for program usage can be conveniently saved in program file elements, as shown in Figures 3 - 6. Figure 3 shows the commands used for compilation. Any number of subroutines can be compiled in a single run by duplicating the @ FTN statement for each. A relocatable element is automatically cataloged for each routine with the same name as the source element. Compilation output is placed in file LIST4 and routed to a printer via the @ SYM command.

A similar list of commands to invoke the MAP processor is shown in Figure 4. The @ MAP statement includes the name of the element containing the MAP directives, MAP, and the name of the absolute element which is created by the MAP processor, RUN. MAP directives are shown in Figure 5.

Program execution is controlled by the commands shown in Figure 6. File 3 contains the theoretical performance data for the propellant combination to be run. File 4 contains kinetic efficiency data and is optional. If a kinetic efficiency is input (input location 167) the file is not read. User inputs, read from Unit 5, are in element DATACH4. Output is placed in file PRINTCH4. The example shown is for an O_2/CH_4 case; for other propellants the appropriate file names must be used for files 3 and 4. Names of the output file and the element containing user inputs are arbitrary and may be selected by the user.

```
100 @FREE LIST4
110 @DELETE,C LIST4.
120 @ASG,PU LIST4.,F//TRK/640
130 @BRKPT PRINT$/LIST4
140 @ADD (FILE QUALIFIER)*BALANCE.LTRS
400 @FTN,FLZ (FILE QUALIFIER)*BALANCE.AMAIN
410 @FTN,FLZ (FILE QUALIFIER)*BALANCE.DATARD
460 @BRKPT PRINT$
470 @FREE LIST4
480 @SYM,U LIST4,,(PRINTER CODE)
```

FIGURE 3. COMPILATION JCL

```
110 @FREE LINKLIST
120 @DELETE,C LINKLIST.
130 @ASG,PU LINKLIST.,F//TRK/640
140 @BRKPT PRINT$/LINKLIST
150 @ADD (FILE QUALIFIER)*BALANCE.LETTERS
160 @MAP,L (FILE QUALIFIER)*BALANCE.MAP,(FILE QUALIFIER)*BALANCE.RUN
170 @BRKPT PRINT$
180 @FREE LINKLIST
190 @SYM,U LINKLIST,,(PRINTER CODE)
```

FIGURE 4. MAP PROCESSOR JCL

```
100 LIB*. . . . . . . . . . .
110 IN (FILE QUALIFIER)*BALANCE.AMAIN
120 IN (FILE QUALIFIER)*BALANCE.BDATA
130 IN (FILE QUALIFIER)*BALANCE.CSIS
140 IN (FILE QUALIFIER)*BALANCE.CSTAR1
150 IN (FILE QUALIFIER)*BALANCE.CSUBF
160 IN (FILE QUALIFIER)*BALANCE.CURVES
170 IN (FILE QUALIFIER)*BALANCE.DATARD
180 IN (FILE QUALIFIER)*BALANCE.DBLGIP
190 IN (FILE QUALIFIER)*BALANCE.DELTAD
200 IN (FILE QUALIFIER)*BALANCE.DUMPER
210 IN (FILE QUALIFIER)*BALANCE.EFF
220 IN (FILE QUALIFIER)*BALANCE.EFFP
230 IN (FILE QUALIFIER)*BALANCE.EHCABC
240 IN (FILE QUALIFIER)*BALANCE.EST
250 IN (FILE QUALIFIER)*BALANCE.EXPL
260 IN (FILE QUALIFIER)*BALANCE.GIP4
270 IN (FILE QUALIFIER)*BALANCE.IMPL
280 IN (FILE QUALIFIER)*BALANCE.IMPULS
290 IN (FILE QUALIFIER)*BALANCE.INTRP
300 IN (FILE QUALIFIER)*BALANCE.KINEFF
310 IN (FILE QUALIFIER)*BALANCE.MAIND
320 IN (FILE QUALIFIER)*BALANCE.OPT
330 IN (FILE QUALIFIER)*BALANCE.PMPCNV
340 IN (FILE QUALIFIER)*BALANCE.PRINT
350 IN (FILE QUALIFIER)*BALANCE.PROCES
360 IN (FILE QUALIFIER)*BALANCE.PRPRP
370 IN (FILE QUALIFIER)*BALANCE.PUMPD
380 IN (FILE QUALIFIER)*BALANCE.REGEN
390 IN (FILE QUALIFIER)*BALANCE.TEMP
400 IN (FILE QUALIFIER)*BALANCE.TRBN1D
410 IN (FILE QUALIFIER)*BALANCE.ZERO
420 END
```

* LIB STATEMENT MAY BE REQUIRED, DEPENDING ON INSTALLATION.

FIGURE 5. MAP DIRECTIVES

```
100 @FREE PRINTCH4
110 @DELETE,C PRINTCH4.
120 @ASG,PU PRINTCH4.,F//TRK/640
130 @USE 3,02CH4ODE
140 @USE 4,02CH4KIN
150 @BRKPT PRINT$/PRINTCH4
160 @ADD BALANCE.LTR
170 @XQT,F BALANCE.RUN
180 @ADD BALANCE.DATACH4
190 @BRKPT PRINT$
200 @FREE PRINTCH4
```

FIGURE 6. Execution JCL

DESCRIPTION OF INPUT DATASETS

This program uses the following input files:

File 3: Propellant performance data file (format 6E12.6)

File 4: Propellant kinetic efficiency data (format 6E12.6)

File 5: User specifications and design inputs (free-field format)

FILE 3 - Performance Data File

This file contains a table of theoretical (ODE) specific impulse and characteristic velocity data. C* is a function of chamber pressure, mixture ratio, and fuel enthalpy. I_s is a function of chamber pressure, mixture ratio, fuel enthalpy, and nozzle area ratio.

The first card image (line) of the file contains integer data which describe the size of the table. The data on this line are:

MR: Number of mixture ratio values contained in the table;

IPC: Number of chamber pressure values contained in the table;

IHF: Number of enthalpy values contained in the table;

IEPS: Number of area ratio values contained in the table.

The format of the first line is:

2(I2,1X),I1,1X,I2).

Subsequent lines contain the values of enthalpy, mixture ratio, and chamber pressure in ascending monotonic order.
Characteristic velocity values follow beginning with the C* corresponding to the first value of H, the first value of MR, and the first Pc. The next C* value corresponds the first value of H, first value of MR, and the second value of Pc. The table is completed in this manner.

Specific impulse data follow the final value of C* and follow a similar pattern, except that area ratio is now the most quickly varying variable. Note that this scheme causes both C* and I_s to be grouped into "sub-tables" which correspond to enthalpy levels.

Area ratio data are placed last in the file, immediately after the final I_s value.

The integer values describing the table size are placed in common block TABSIZ and the rest of the table is in common block IS. (Common blocks are described on page 55).

FILE 4 - Kinetic Efficiency Data

File 4 contains the optional tables of kinetic efficiency data as a function of chamber pressure, mixture ratio, and nozzle area ratio.

These separate tables are required, corresponding to nozzle throat radii of .1, 1, and 10 inches. The tables, read into arrays EFF1, EFF2, and EFF3 in common block EFFK, must be in CURVES format (see CURVES subroutine description).

At the time of publication, kinetic files are available only for O_2/H_2 and O_2/CH_4. For other propellants, a user-supplied value must be input at location 167.

FILE 5 - User Input Data

User inputs are read into common block A from file number 5 via subroutine DATARD. This routine permits easy entry and alteration of data. Input is free field, with up to 10 input items per line. Each input line (card image) is configured in the same manner, namely:

Start location   Value 1   Value 2   ---   Value n   /

where Start location is an integer value which specifies the first location within the input array where the subsequent entries will be placed in sequential order;

Value 1 is the value which will be stored in the location specified by Start location ;

Value 2 is the value which will be stored in the location specified by Start location + 1;

Value n is the value which will be stored in the location specified by Start location + n - 1.

Each individual entry is separated from others by a blank space or comma. Decimal points are optional. Each input line must terminate with a slash (/) if it contains less than ten items. Characters which follow the slash are ignored, and may be used as comment or remark entries.

Input data are terminated by:

0/

where '0' (numeric zero) specifies the 'zero location' and causes the next line to be read as an alphanumeric title followed by a return from DATARD. Note that subsequent calls to DATARD will cause input to commence at the point in the file immediately after the last occurrence of "0/" and title line entries, which means that multiple cases can be run.

EXAMPLE:

```
        100   1, 3.2, 7.8, 4 /
line number
```

will cause input location No. 1 to contain the value 3.2,
location No. 2 will contain 7.8,
and location No. 3 will contain 4.0

NOTE: No alphabetic (A-Z) characters may appear to the left of the slash (/).

Items can be skipped by entering multiple commas, e.g.:

```
100   1, 3.2,, 4/
```

will leave location 2 unchanged. Also, identical values can be input using an "*"; the line

```
100   13, 4 * 2000, 5.6, 5E4/
```

will load the value 2000 into locations 13-16. Both the skipped locations and the repeated values count as part of the 10 inputs per line allowed.

SCHEMATIC DESCRIPTION

There are currently seven schematics incorporated into the program, each identified by a code number which is input to select the desired schematic. The code number is a three-digit number with the first digit indicating the cycle, i.e., 101 - 199 for staged combustion cycles, 201 - 299 for expander cycles, and 301 - 399 for gas generator cycles. The schematics are illustrated in Figures 7 - 13 and described below. The numbers on the schematics indicate locations where pressures are calculated and correspond to subscripts in the PRES array (common locations 221 - 250).

Schematic 101 is a conventional staged combustion cycle with fuel-rich preburners. All of the fuel flow is routed from the pump discharge to the thrust chamber coolant jacket. The schematic shows a parallel cooling circuit, with part of the fuel going to the nozzle and part to the combustor. A series cooling circuit can also be specified, in which case all the fuel passes through both the nozzle and combustor cooling jackets. An ablative chamber can be modeled by inputting 0.0 in the input locations provided for user overrides of the built-in pressure drop and heat load calculations (locations 186-190). The fuel leaving the cooling jackets is all routed to the preburners, except for the user-specified bypass flow. The bypass flow can be specified for providing injector and hot gas manifold cooling, to provide for cycle power margin to insure reaching design thrust levels, to provide cooling for other cooled components, such as turbine blades, or other uses. (In the SSME, for example, only the nozzle coolant flow goes to the preburner, the combustor coolant is used to drive a boost pump turbine.)

The oxidizer flow routed to the preburners is calculated from the known fuel preburner flow and the user-specified turbine inlet temperatures. The remainder of the oxidizer goes directly from the pump discharge to the main injector. Kick pump options may be selected for both the oxidizer and fuel pumps. On the oxidizer side, the kick pump (input location 116) raises the

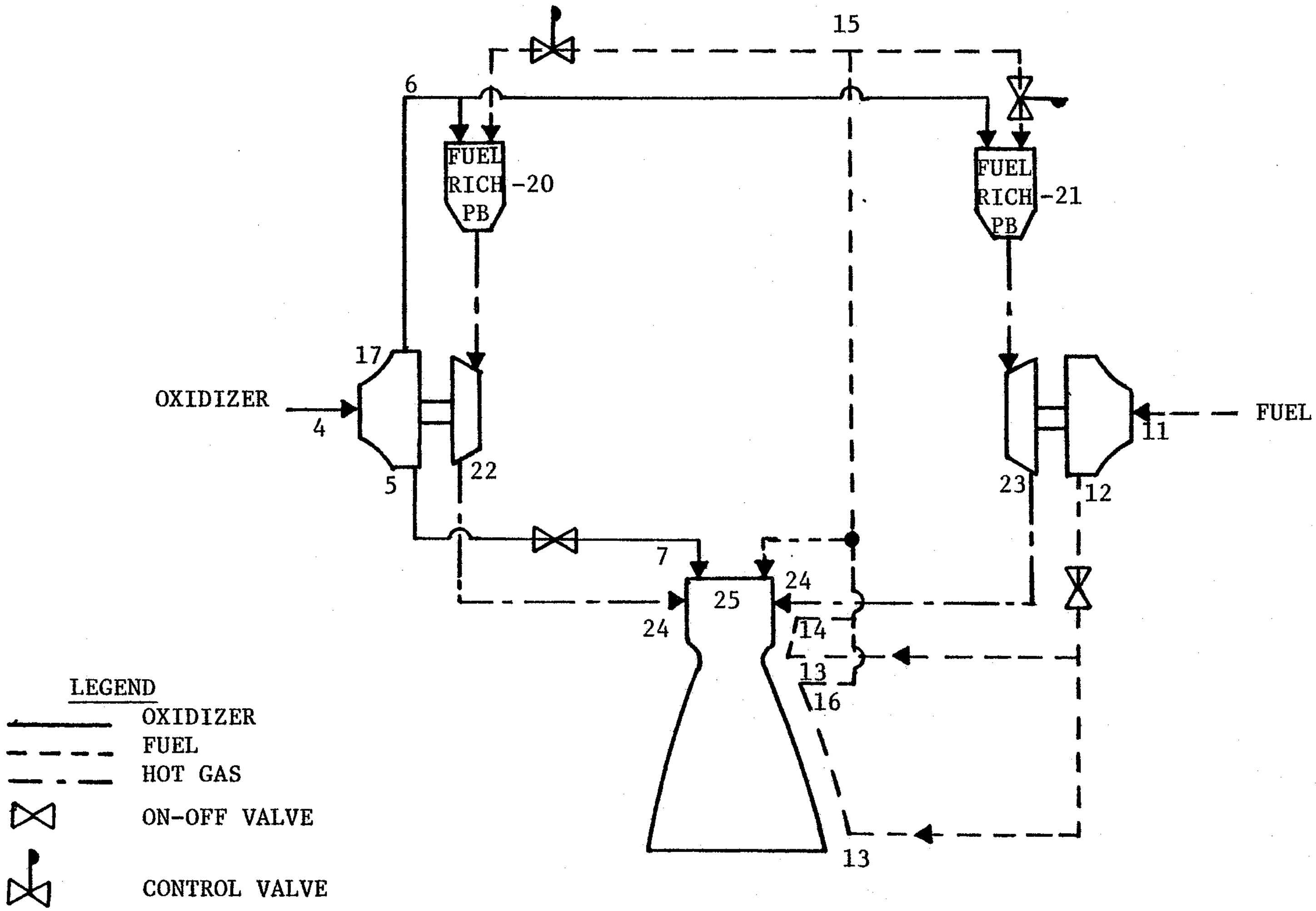

FIGURE 7. SCHEMATIC 101-STAGED COMBUSTION CYCLE

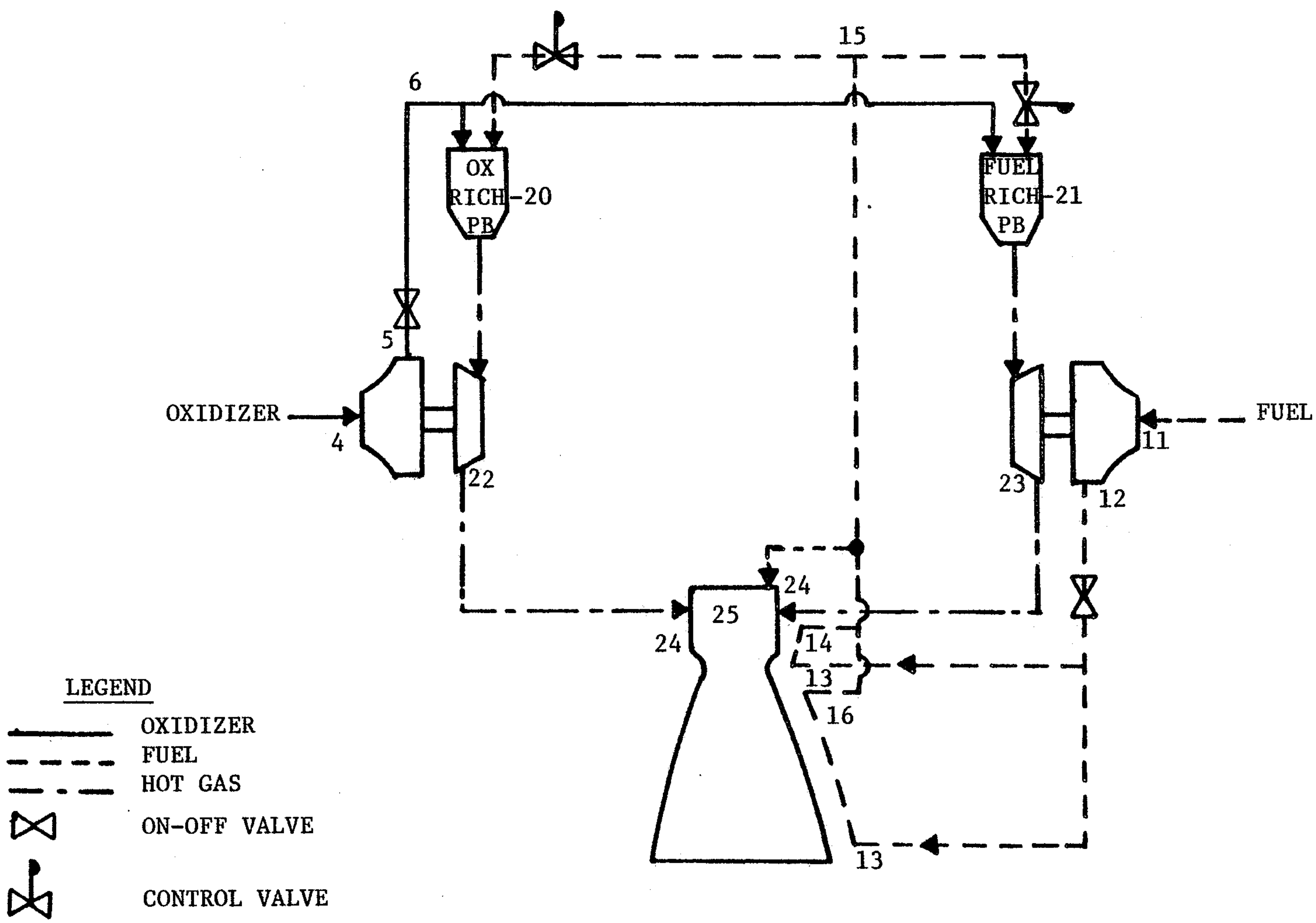

FIGURE 8. SCHEMATIC 102-STAGED COMBUSTION CYCLE

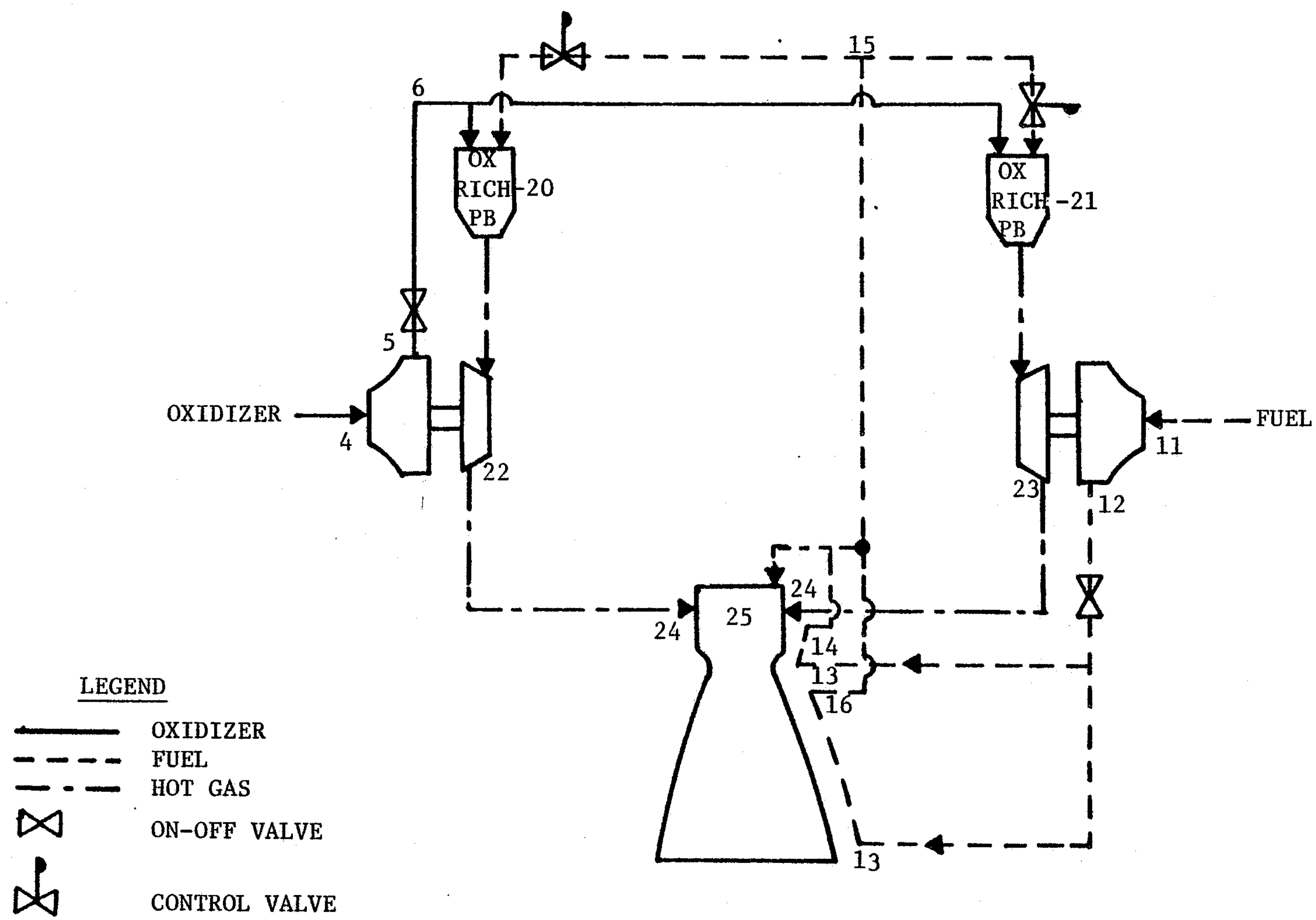

FIGURE 9. SCHEMATIC 103-STAGED COMBUSTION CYCLE

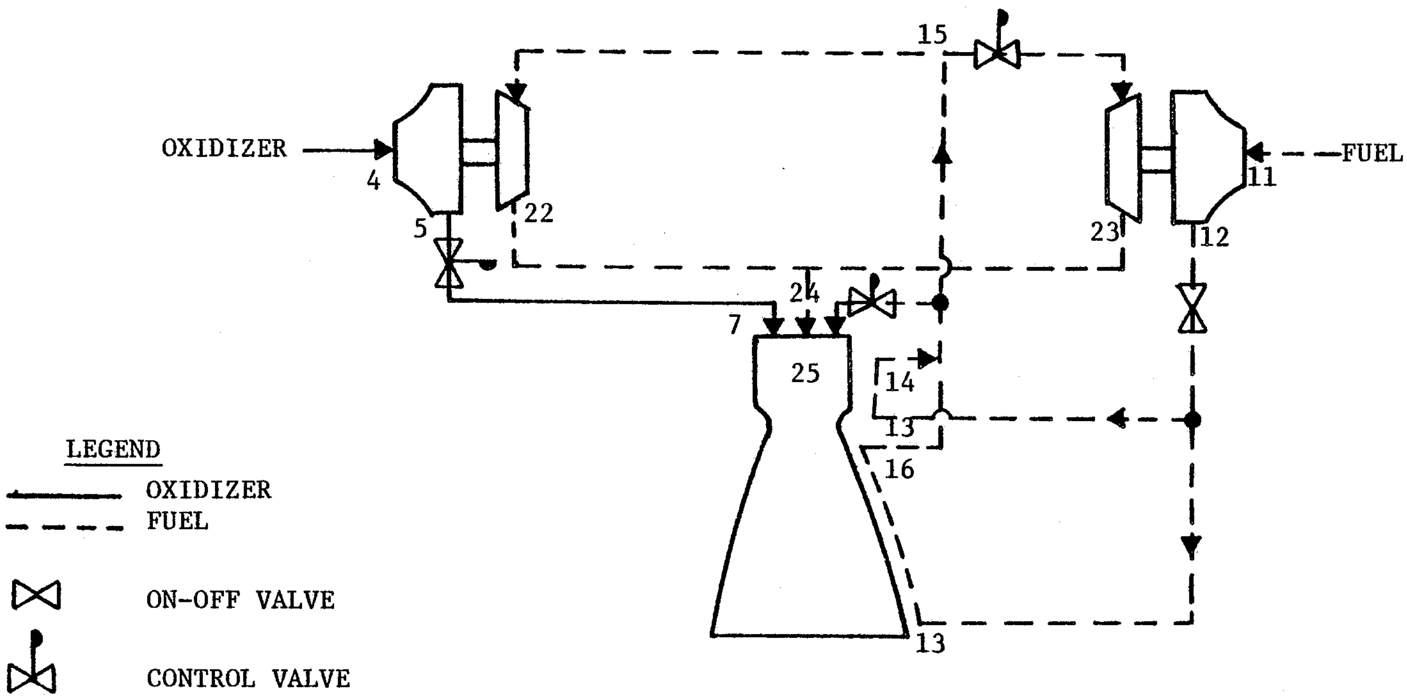

FIGURE 10. SCHEMATIC 201-EXPANDER CYCLE

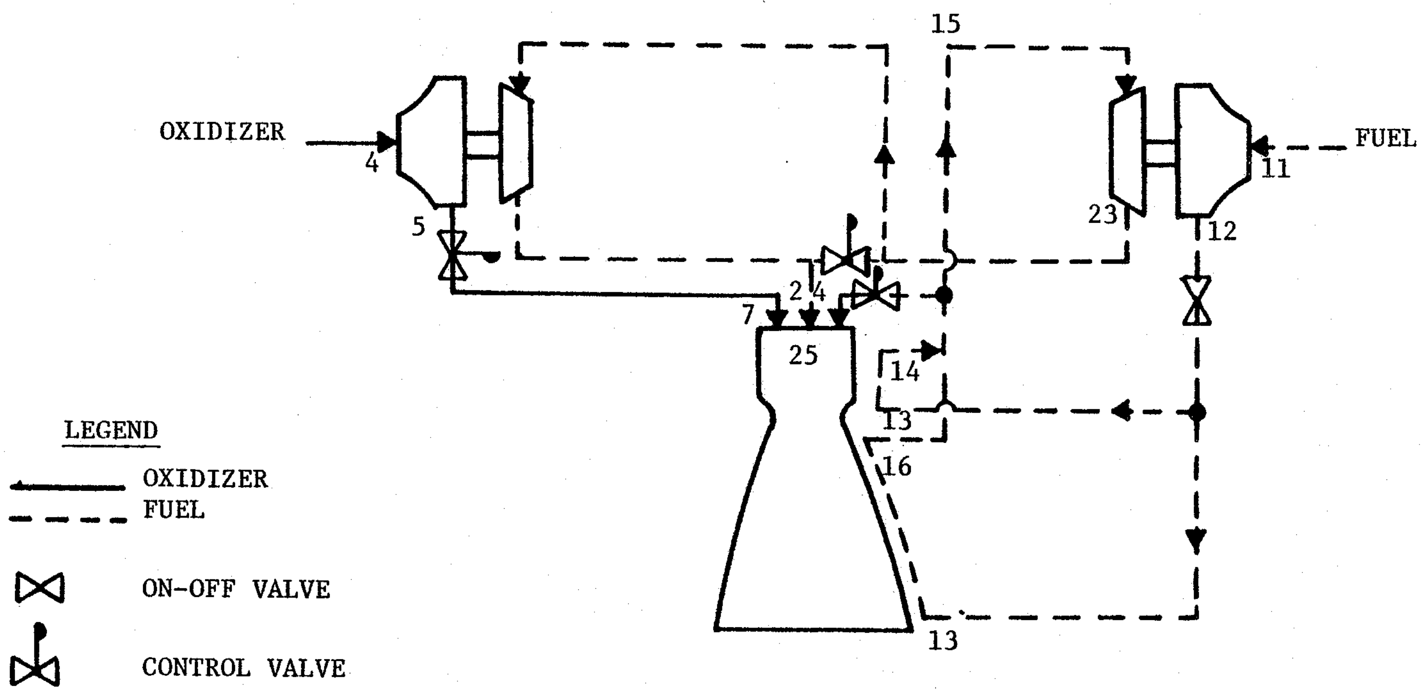

FIGURE 11. SCHEMATIC 202-EXPANDER CYCLE

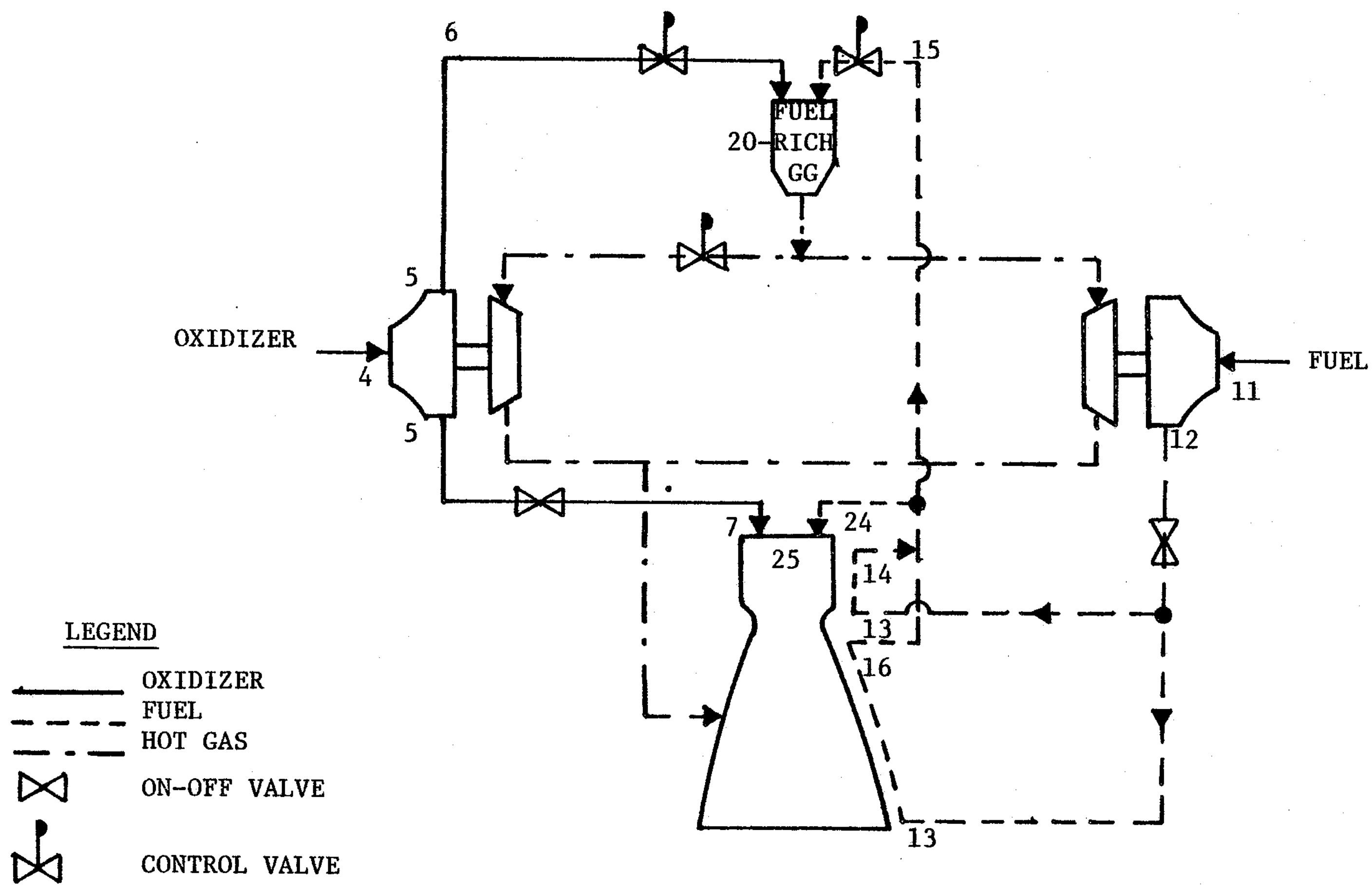

FIGURE 12. SCHEMATIC 301-GAS GENERATOR CYCLE

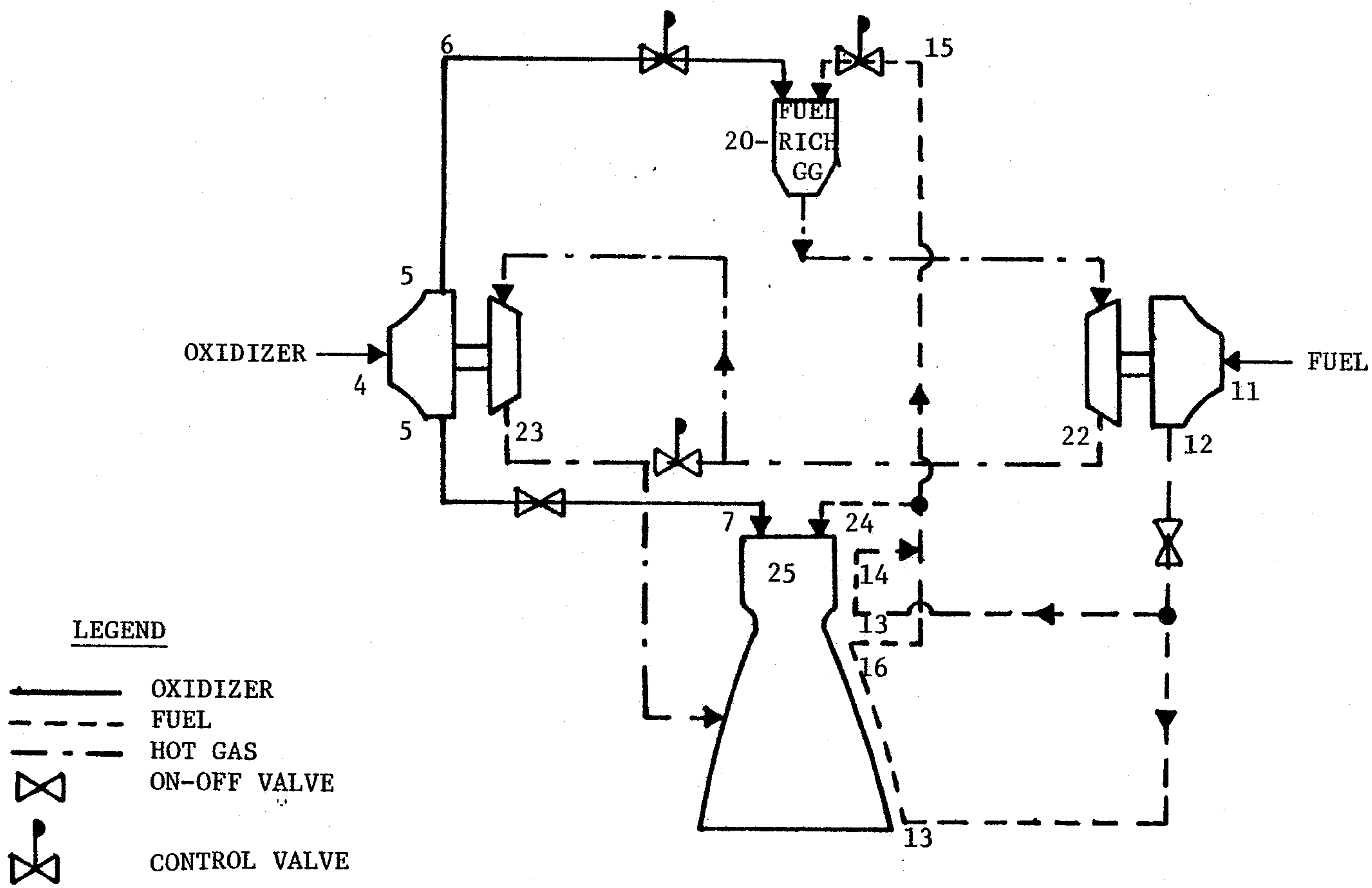

FIGURE 13. SCHEMATIC 302-GAS GENERATOR CYCLE

preburner flow to the higher pressure required at the preburner inlet. On the fuel side, the kick pump (input location 115) raises the combustor coolant flow to the higher pressure required to account for the combustor pressure drop.

Schematic 102 is a staged combustion cycle with mixed preburners, an oxidizer-rich preburner driving the oxidizer turbine and a fuel-rich preburner driving the fuel turbine. In this cycle, all the propellants are burned in the preburners except the user-specified fuel bypass. A fuel kick pump can be specified as for schematic 101.

Schematic 103 is a staged combustion cycle with oxidizer-rich preburners. All the oxidizer flow goes to the preburners and the preburner fuel flow is calculated to provide the desired turbine inlet temperatures. In this case a fuel kick pump can be specified to raise the preburner flow to preburner pressures.

Schematic 201 is an expander cycle with parallel turbines. The oxidizer flow is routed directly to the main injector and all the fuel, less the bypass flow, drives the turbines.

Schematic 202 is an expander cycle with series turbines. The fuel leaving the coolant jacket passes through the fuel turbine and into the oxidizer turbine. Provision is made to bypass fuel around the oxidizer turbine in the event that passing the total fuel flow through the oxidizer turbine would result in a pressure ratio less than the minimum specified (input location 82).

Schematic 301 is a gas generator cycle with parallel turbines. The turbine exhaust flow is assumed to be expanded from the turbine exit pressure to the main nozzle exit pressure and thus contributes to the engine thrust level. No particular method for doing this is assumed but possibilities include injecting the turbine exhaust flow into the main chamber, placing a small thrust chamber at the turbine exits, or installing a small annular thrust chamber around the exit of the main nozzle. The gas generator chamber pressure is limited to the value that could be achieved with the pump discharge pressures set by the main chamber pressure. It would seldom, if ever, be desirable to allow the gas generator to establish pump discharge pressures.

Schematic 302 is a gas generator cycle with series turbines. The fuel turbine pressure ratio is set by the optimizer and the oxidizer turbine pressure ratio is set by the available pressures or the input maximum pressure ratio (input location 89), whichever is less.

USER INPUT SELECTION

User inputs defining the engine configuration and options are in common block A, along with most of the parameters calculated by the program. All references to input location number refer to the location in common block A. Inputs are somewhat intermixed with outputs so the user should become familiar with the common block structure. The following paragraphs summarize those inputs which change most often and should be checked prior to each run. Where appropriate, reference is made to explanatory notes at the end of the Common Block Description section.

Location 1, Engine vacuum thrust

Location 2, Nozzle expansion area ratio

Location 3, Chamber pressure: If the chamber pressure maximization option is selected, this value is used as the initial guess. A value of approximately half the expected maximum chamber pressure is recommended since this will normally provide a wide latitude in selecting the other initial guesses.

Location 4, Engine mixture ratio

Location 5, Fuel bypass fraction: This value is relevant only for staged combustion and expander cycles.

Location 6, Propellant combination: Propellant combination is selected by inputting a number from 1 to 6, as follows:

1 O_2/H_2
2 O_2/CH_4
3 O_2/RP-1
4 O_2/C_3H_8 (NBP)
5 O_2/C_3H_8 (Subcooled)
6 NTO/MMH

The subcooled C_3H_8 is at the same temperature as the O_2 (163 R) which eliminates the need for insulation between the vehicle propellant tanks and increases the fuel density 26% over the density at 416 R (normal boiling point).

Location 7, Engine Cycle: This input selects the cycle and schematic. The options are listed below and described in the Schematic Description section.

101 Staged combustion cycle: fuel-rich preburners
102 Staged combustion cycle: mixed preburners
103 Staged combustion cycle: oxidizer-rich preburners
201 Expander cycle: parallel turbines
202 Expander cycle: series turbines
301 Gas generator cycle: parallel turbines
302 Gas generator cycle: series turbines

Location 11, Minimization objective flag: See Note 4

Location 12, Initial guess check flag: See Note 5

Locations 77-89, Optimizer explicit limits: Except for the limits on turbine admission fractions, the lower limit on turbine pressure ratio, and the upper limit on gas generator cycle turbine pressure ratio, it is not generally desirable to limit the optimizer variables explicitly. Somewhat realistic limits are required, however, to avoid mathematical errors as described in the Diagnostic Messages section. Changes to these limits are most important when changing engine cycle, particularly the upper and lower limits on turbine pressure ratio. The lower limit on turbine admission fraction may also be affected if the turbine type is changed.

Location 100-101, Turbine type flags: See subroutine TRBN1D description for guidance in selecting the turbine types.

Locations 106-107, Turbine inlet temperatures.

Locations 117-118, Number of pump stages: In most cases, a single stage will be adequate for all propellants except CH_4, which will require one to three stages, and H_2, which will require two or more stages. See the Output Interpretation section for further information.

Location 140, GG cycle turbine exit pressure: This input affects only the gas generator cycle and is typically 20-200 psia. Higher values result in higher turbine exhaust specific impulse, and smaller turbine sizes but may restrict turbine pressure ratios. Lower values increase the turbine size which raises performance at low thrust levels. This parameter should be optimized for peak performance.

Locations 151-156, Initial guesses on optimizer independent variables: Program operation requires a set of initial guesses which do not violate any implicit constraints. For an arbitrary case, these guesses are determined by trial and error; for similar cases, the same guesses can be used with little or no modification.

Location 166, C* efficiency: This input is empirical and varies with propellant combination, thrust level, and chamber pressure. (See Note 16)

Except for the initial guesses on optimizer independent variables, the program is not particularly sensitive to values of input variables, in the sense that small changes in input values have a large effect on calculated variables. The initial guesses are sensitive only because a starting point is required which does not violate any implicit constraints.

Since the program has been recently revised there are few, if any, input combinations which can be used to "trick" the program into analyzing configurations not originally incorporated. A possible exception, described in the previous section, is the use of the fuel bypass fraction to account for coolant flow to the turbine blades or other components.

OUTPUT INTERPRETATION

Each program output should be examined to ensure that the results are reliable. Output examples are shown in the Sample Run section. The first part of the printout summarizes the design options in effect and is followed by the optimizer printout which shows the value of the object function (variable being maximized or minimized) and optimizer independent variables as the optimization progresses. If an implicit constraint is violated using the initial guesses input for the optimizer variables a message will be printed after the first optimizer iteration and no other optimizer printout will occur. Otherwise the optimizer variables will be printed every 10 iterations and if no error messages follow the final optimizer printout a successful balance has been achieved. The number of optimizer iterations required may be as few as 70-80, or as many as 300-400, depending on both the case being modeled and the optimizer termination tolerance specified. If the object function is still changing significantly when the case terminates the tolerance should be decreased. If there is little change in many iterations the tolerance can be increased.

The following parameters in the formatted output should also be examined.

- COOLANT BYPASS-ACTUAL: This value should be very close to the bypass specified in input location 5 (staged combustion and expander cycles). If less, the message "ERROR DETECTED NUMBER-60" will probably appear at the end of the optimizer printout (see diagnostic messages). If significantly greater, the optimizer termination tolerance should be tightened.

- PUMP ROTATING SPEED: If the pump speeds are very close to the explicit limits, the limits should be relaxed.

- PUMP EFFICIENCY: The pump efficiency is primarily a function of the pump specific speed. If both values are low, the number of pump stages or the pump speed should be increased. A pump efficiency of .23 indicates that the efficiency data limits have been exceeded and the specific speed is probably too low (<400). If the efficiency and specific speed are high, it may be possible to reduce the number of pump stages without significant penalty.

- TURBINE EFFICIENCY AND VELOCITY RATIO: The turbine efficiency and velocity ratio will indicate whether the selected turbine types are appropriate. See the TRBN1D subroutine description for further information on selecting turbine types.

RANGE OF OPERATION

There are few inherent limitations on the range of operating conditions that can be modeled by the program. Other than turbomachinery limits, the primary limitations are those resulting from available propellant-combination-related data. These limits are summarized below:

- Turbomachinery - The pump and turbine analyses in the program are for conventional centrifugal-flow pumps and gas turbines. At very low thrust levels, other alternatives not presently modeled by the code may be preferable; e.g., partial emission of positive-displacement pumps, and drive methods other than gas turbines. The lower limit on thrust cannot be easily established since it depends on propellant combination, pressure levels, and other factors, but it is suggested that below thrust levels of approximately 500-5000 lbs, the output be examined closely. It is inherently more difficult to achieve high turbomachinery efficiencies as power levels decrease but, at some point, alternative designs will provide better performance.

- Input propellant data - The theoretical performance and kinetic efficiency data read by the program will limit operational ranges. Although the interpolation routines will extrapolate, the user should be aware of the ranges covered by the input data.

- Thrust chamber cooling - The heat transfer data currently in the program cover only limited operating ranges for a few propellant combinations, as described in the REGEN subroutine writeup. Provision is made, however, for user inputs of combustor and nozzle pressure drops and heat loads in input locations 186-190.

- Turbine drive gas properties - Turbine drive gas properties in the program are summarized in the BLOCK DATA and proces subroutine descriptions. User overrides for these properties are also provided for, in locations 181-185.

SAMPLE RUN

A sample run is included to illustrate the input data file setup, program execution, and program output. Two cases were selected; the default case, which is a 500K O_2/CH_4 staged combustion engine, and a similar engine with a gas generator cycle.

PROGRAM INPUT

The input data file for the sample run is shown in Figure 14. The default case requires only two lines, one to terminate data input and a title line. The GG cycle case inputs are shown in the data file listing with brief comments describing each. The schematic flag and optimizer minimization flag must be changed to reflect the cycle change and the desired chamber pressure, rather than an initial guess, must be input. The turbine type and the initial guess and limits on turbine pressure ratio were changed to values appropriate for the GG cycle. The oxidizer kick pump flag was turned off since the kick pump option applies only to staged combustion cycles and the number of fuel pump stages was reduced from 3 to 2 due to the lower pump discharge pressures expected for this cycle. The program was executed with the JCL shown in Figure 15, with the output written to file PRINTCH4.

PROGRAM OUTPUT

The program output is shown starting on page 40. The staged combustion cycle balance is shown first and examination of the output variables suggested in the User Instruction section indicates that the only questionable value is the oxidizer kick pump efficiency of 43%. The low specific speed of 370 suggests that a two-stage kick pump would provide higher performance, although the effect on maximum chamber pressure would be small due to the low horsepower requirement of the kick pump.

```
100 0/
110  02/CH4 DEFAULT ENGINE BALANCE
120 3,3500/ CHAMBER PRESSURE
130 7,301/ GG CYCLE SCHEMATIC FLAG
140 11,1/ MINIMIZATION OBJECTIVE FLAG
150 82,5/ TURBINE PRESSURE RATIO LOWER LIMIT
160 89,30/ TURBINE PRESSURE RATIO UPPER LIMIT
170 100,2,2/ TURBINE TYPE FLAGS
180 116,0/ OXIDIZER KICK PUMP FLAG
190 117,2/ NO. OF FUEL PUMP STAGES
200 156,15/ TURBINE PRESSURE RATIO INITIAL GUESS
210 0/
220  02/CH4 GAS GENERATOR CYCLE
```

FIGURE 14. SAMPLE RUN INPUT DATA FILE

```
100 @FREE PRINTCH4
110 @DELETE,C PRINTCH4.
120 @ASG,PU PRINTCH4.,F//TRK/640
130 @USE 3,02CH40DE
140 @USE 4,02CH4KIN
150 @BRKPT PRINT$/PRINTCH4
160 @ADD BALANCE.LTR*
170 @XQT,F BALANCE.RUN
180 @ADD BALANCE.DATACH4
190 @BRKPT PRINT$
200 @FREE PRINTCH4
```

* THIS ELEMENT INVOKES THE @ BFL PROCESSOR TO PRING A BANNER AT THE BEGINNING OF THE OUTPUT.

FIGURE 15. SAMPLE RUN EXECUTION JCL

The gas generator cycle balance follows the staged combustion cycle balance and also shows acceptable results. The thrust chamber mixture ratio of 4.012 is close enough to the maximum value of 4.0 in the theoretical specific impulse table but the delivered specific impulse could be increased by lowering the input engine mixture ratio. The turbine exit pressure could also be raised, without seriously affecting turbine efficiency, which would increase the turbine exhaust performance and reduce the turbine size.

O_2/CH_4 DEFAULT ENGINE BALANCE

STEADY STATE DESIGN AND ENGINE BALANCE PROGRAM

DESIGN OPTIONS IN EFFECT:

		OXIDIZER	FUEL
MAIN TURBOPUMP-			
NUMBER OF CENTRIFUGAL STAGES		1.	3.
TURBINE TYPE FLAG	(1.=1 ROW 2.=2 ROW 3.=50% REACTION 4.=2 STAGE)	4.	4.
TURBINE SIZE FLAG	(0.=2 INCH DIA. 1.=3+ INCH DIA.)	1.	1.
KICK PUMP FLAG-	(0.=NO +.=YES-NO. OF STAGES-)	1.	0.
SCHEMATIC FLAG-		101.	
MINIMIZATION OBJECTIVE FLAG-	(0.=COOLANT PUMP PD 1.=SECONDARY FLOW -2.=P(C))	-2.	
INITIAL GUESS CHECK FLAG-	(0.=FULL OPTIMIZATION 1.=1 ITERATION ONLY)	0.	
OXIDIZER TYPE FLAG	(1.=DOUBLE ENTRY 0.=SINGLE ENTRY)	0.	

```
                              ( A )                                           (    B    )
   (    C    )  (    D    )  (    E    )  (    F    )  (    G    )  (    H    )
   (    I    )
     A = NUMBER OF SUCCESSFUL ITERATIONS
     B = PARAMETER CURRENTLY BEING MINIMIZED:
              FOR D(11)=1.0 - TOTAL TURBINE FLOW RATE
              FOR D(11)=0.0 - MAIN FUEL PUMP DISCHARGE PRESSURE
             (FOR D(11)=0.0 FLOW RATE IS MINIMIZED FIRST THEN PD IS MINIMIZED)
     C = MAIN FUEL PUMP SPEED
     D = MAIN OXIDIZER PUMP SPEED
     E = MAIN FUEL TURBINE ADMISSION
     F = MAIN OXIDIZER TURBINE ADMISSION
     G = COOLANT FLOW SPLIT:  W(COMB)/W(TOTAL)
     H = MAIN FUEL TURBINE PRESSURE RATIO
     I = CHAMBER PRESSURE


   NO. OF SUCCESSFUL ITERATIONS=   1     PARAMETER BEING MINIMIZED=  .211753+003
    .150000+005  .600000+004  .999000+000  .999000+000  .500000+000  .179000+001

   NO. OF SUCCESSFUL ITERATIONS=   1     PARAMETER BEING MINIMIZED= -.150000+004
    .177996+005  .797725+004  .971807+000  .971807+000  .500000+000  .205823+001
  .150000+004

   NO. OF SUCCESSFUL ITERATIONS=  10     PARAMETER BEING MINIMIZED= -.215864+004
    .112290+005  .656883+004  .930564+000  .927605+000  .507613+000  .203699+001
  .215864+004

   NO. OF SUCCESSFUL ITERATIONS=  20     PARAMETER BEING MINIMIZED= -.202980+004
    .145430+005  .740080+004  .930800+000  .944520+000  .496775+000  .202747+001
  .202980+004

   NO. OF SUCCESSFUL ITERATIONS=  30     PARAMETER BEING MINIMIZED= -.236470+004
    .137332+005  .819943+004  .940397+000  .939647+000  .497185+000  .211722+001
  .236470+004

   NO. OF SUCCESSFUL ITERATIONS=  40     PARAMETER BEING MINIMIZED= -.268967+004
    .169575+005  .914484+004  .942218+000  .940930+000  .499561+000  .228159+001
  .268967+004

   NO. OF SUCCESSFUL ITERATIONS=  50     PARAMETER BEING MINIMIZED= -.311240+004
    .292267+005  .105690+005  .954027+000  .955613+000  .497885+000  .229281+001
  .311240+004

   NO. OF SUCCESSFUL ITERATIONS=  60     PARAMETER BEING MINIMIZED= -.320656+004
    .299192+005  .111281+005  .956425+000  .954315+000  .500642+000  .234082+001
  .320656+004

   NO. OF SUCCESSFUL ITERATIONS=  70     PARAMETER BEING MINIMIZED= -.324929+004
    .315162+005  .114558+005  .965712+000  .959630+000  .499260+000  .233726+001
  .324929+004

   NO. OF SUCCESSFUL ITERATIONS=  80     PARAMETER BEING MINIMIZED= -.330583+004
```

```
 .315119+005  .123380+005  .983552+000  .974752+000  .501195+000  .219755+001
.330583+004

NO. OF SUCCESSFUL ITERATIONS=  90     PARAMETER BEING MINIMIZED= -.339663+004
 .325161+005  .131852+005  .984455+000  .963221+000  .499997+000  .195694+001
.339663+004

NO. OF SUCCESSFUL ITERATIONS= 100     PARAMETER BEING MINIMIZED= -.339989+004
 .337462+005  .131889+005  .984552+000  .972197+000  .502178+000  .202782+001
.339989+004

NO. OF SUCCESSFUL ITERATIONS= 110     PARAMETER BEING MINIMIZED= -.342471+004
 .334078+005  .135659+005  .985962+000  .974199+000  .501603+000  .195265+001
.342471+004

NO. OF SUCCESSFUL ITERATIONS= 120     PARAMETER BEING MINIMIZED= -.345181+004
 .332364+005  .139536+005  .981620+000  .974176+000  .501487+000  .203610+001
.345181+004

NO. OF SUCCESSFUL ITERATIONS= 130     PARAMETER BEING MINIMIZED= -.349690+004
 .320413+005  .145247+005  .984404+000  .983460+000  .501615+000  .214335+001
.349690+004

NO. OF SUCCESSFUL ITERATIONS= 140     PARAMETER BEING MINIMIZED= -.355513+004
 .309797+005  .151065+005  .986189+000  .991418+000  .501607+000  .219867+001
.355513+004

NO. OF SUCCESSFUL ITERATIONS= 150     PARAMETER BEING MINIMIZED= -.358616+004
 .302252+005  .156405+005  .982830+000  .991355+000  .502038+000  .222048+001
.358616+004

NO. OF SUCCESSFUL ITERATIONS= 160     PARAMETER BEING MINIMIZED= -.361723+004
 .300921+005  .161717+005  .983612+000  .989451+000  .502221+000  .230074+001
.361723+004

NO. OF SUCCESSFUL ITERATIONS= 170     PARAMETER BEING MINIMIZED= -.363688+004
 .299858+005  .166503+005  .988591+000  .991504+000  .502699+000  .224375+001
.363688+004

NO. OF SUCCESSFUL ITERATIONS= 180     PARAMETER BEING MINIMIZED= -.365207+004
 .305452+005  .169099+005  .988920+000  .991019+000  .502689+000  .223274+001
.365207+004

NO. OF SUCCESSFUL ITERATIONS= 190     PARAMETER BEING MINIMIZED= -.365844+004
 .304346+005  .170272+005  .988918+000  .990523+000  .503657+000  .219895+001
.365844+004

NO. OF SUCCESSFUL ITERATIONS= 200     PARAMETER BEING MINIMIZED= -.365718+004
 .304869+005  .169749+005  .989233+000  .989721+000  .502844+000  .220363+001
.365718+004

NO. OF SUCCESSFUL ITERATIONS= 210     PARAMETER BEING MINIMIZED= -.365833+004
 .305407+005  .170167+005  .990138+000  .991553+000  .503660+000  .221294+001
.365833+004

NO. OF SUCCESSFUL ITERATIONS= 220     PARAMETER BEING MINIMIZED= -.366100+004
 .306297+005  .170347+005  .987609+000  .989153+000  .503711+000  .219077+001
```

.366100+004

NO. OF SUCCESSFUL ITERATIONS= 230 PARAMETER BEING MINIMIZED= -.366086+004
.306294+005 .170346+005 .988485+000 .990154+000 .503760+000 .219810+001
.366086+004

NO. OF SUCCESSFUL ITERATIONS= 240 PARAMETER BEING MINIMIZED= -.366339+004
.308296+005 .170761+005 .987849+000 .990093+000 .503866+000 .218752+001
.366339+004

NO. OF SUCCESSFUL ITERATIONS= 250 PARAMETER BEING MINIMIZED= -.366426+004
.309163+005 .170971+005 .987540+000 .989584+000 .503921+000 .218293+001
.366426+004

```
COMMON-BLOCK /A/

  1 5.0000+005 3.5000+001 1.5000+003 3.5000+000 1.0000-001 2.0000+000 1.0100+002  .0000      .0000      .0000
 11-2.0000+000  .0000     2.0000+003 1.4000+003 6.0000+003  .0000     3.0000-002 3.0000-002 1.0000+000 1.0000+000
 21 1.8000+006 1.0000+006 8.0000-001 8.0000-001 1.6000+003 1.6000+003 1.6000+003 1.6000+003 1.0000+006  .0000
 31 4.0000+002 4.0000+002 2.2000+003 2.2000+003 2.0000+000 2.0000+000 1.0000+002 1.0000+002  .0000      .0000
   LOCATIONS    41 THRU    70 CONTAIN   .000000
 71  .0000      .0000      .0000      .0000      .0000      .0000     5.0000+003 5.0000+003 9.0000-001 9.0000-001
 81 4.9000-001 1.1500+000  .0000     5.0000+004 5.0000+004 1.0000+000 1.0000+000 5.1000-001 5.0000+000  .0000
 91  .0000      .0000      .0000     1.3000+000 1.0000-004 1.0000+000 1.6000+003 2.5000-001 4.0000+010 4.0000+000
101 4.0000+000 2.0000+000 9.0000-001 1.0000+000 1.0000+000 2.0000+003 2.0000+003 6.0000-001  .0000      .0000
111 3.0000+001 3.0000+001 1.5300+001 1.5300+001  .0000     1.0000+000 3.0000+000 1.0000+000  .0000      .0000
121 1.0000-001 1.0000-001  .0000      .0000     3.5000-001 3.5000-001  .0000      .0000      .0000      .0000
131 5.0000-003 1.0000-002 5.0000-002 1.0000-001 1.5000-001 8.0000-002  .0000      .0000      .0000     3.0000+001
141 1.5676+002 1.5432+002 1.4960+003 1.4960+002 2.0000-001 1.0000+002  .0000      .0000      .0000      .0000
151 1.5000+004 6.0000+003 9.9900-001 9.9900-001 5.0000-001 1.7900+000 1.8367+003 1.8582+003 7.6752+002 7.5968+002
161  .0000      .0000     1.0000-004 2.0000+003 2.0000+003 9.8000-001  .0000     1.1390+000 6.8652+002  .0000
171 5.8103+002 4.8572+002 5.3375+002  .0000      .0000      .0000      .0000      .0000      .0000      .0000
   LOCATIONS   181 THRU   190 CONTAIN   .000000
191 9.0000-001 9.8200-001  .0000      .0000      .0000     3.1107+002 1.0888+003 2.7989+002 1.0547+002 7.1335+001
201 1.9128+000 5.0000+005 3.5000+000 3.5719+002  .0000     2.6380+001 7.1230+001 1.6043+001 3.1999+001-2.1390+001
211-3.1020+000 2.0000+000 2.0000+000 1.2331+002  .0000      .0000      .0000      .0000      .0000      .0000
221 3.0000+001 3.0931+001 2.1829+000 3.0000+001 4.3763+003 1.0332+004 4.3109+003 3.0000+001 8.3518+001 2.1829+000
231 3.0000+001 1.2340+004 1.2156+004 1.0660+004 1.0606+004 1.2006+004 1.0489+004 1.2340+004  .0000     8.7828+003
241 8.7820+003 4.0029+003 4.0029+003 3.9829+003 3.6643+003  .0000      .0000      .0000     4.6878+000 5.9522+000
251 5.5309+004 3.9742+004 6.2304+002 7.4795+002 5.7609+001 5.5589+002 1.0000-001  .0000     7.4456+000 3.8206+001
261  .0000      .0000      .0000      .0000     1.0315+002  .0000     7.7246+002  .0000     4.7378-001 1.0346+001
271 8.7170-001 7.1963-001 1.5605+003 8.7866+003  .0000     8.4557-001 2.0569+004  .0000     7.8423+001 7.5672+002
281 1.0000-001  .0000     5.6051+000 2.1652+001  .0000      .0000      .0000      .0000     1.9115+002  .0000
291 1.1947+003  .0000     5.0491-001 8.8492+000 5.7297-001 6.3340-001 1.2285+003 6.7197+004  .0000     8.2353-001
301 4.6146+004  .0000     3.7683-001 1.6143+001 1.1668+000 8.6064-001 1.0547+002  .0000      .0000     1.1668+000
311 8.6064-001 2.0000+003 2.0000+003  .0000     1.6143+001 3.7683-001  .0000     6.6490-001 8.8838+000 1.5178+002
321 2.5960+004 4.6757-001 4.6757-001 3.0702-001 6.9817+002 3.8145+009 5.0000+000 9.9984+005 7.6799-001 7.6809+000
331 2.3358+002 4.6146+004 8.3159-001 8.3159-001 4.8000-001 1.1492+003 1.9180+010 2.0000+000 1.7977+006 3.5725+001
341 1.9718+001 6.8604+003 5.2926+003 9.0000-001 8.0462-001  .0000      .0000      .0000      .0000      .0000
   LOCATIONS   351 THRU   360 CONTAIN   .000000
361  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     3.0916+004  .0000
371  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     1.7097+004  .0000
381  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     9.8754-001  .0000
391  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     9.8958-001  .0000
401  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     5.0392-001  .0000
411  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     2.1829+000  .0000
421  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     3.1107+002 1.0888+003
431 3.8546+002 3.8536+002  .0000      .0000     1.0024+001  .0000     5.8600+002 2.1895-047 3.8536+002  .0000
441 8.1184+002  .0000     6.0320-001 1.0874+001 1.5572-001 3.1447-001 3.7610+002 1.2357+004 4.3951-001  .0000
451 5.3908+003  .0000    -1.7566+001-1.7566+001 3.5719+002 6.0079+003 3.3098+002 3.7072+002 6.1305+003 3.7683-001
461 3.7683-001-1.8984+001 1.0000+000 9.8000-001 9.9521-001 1.1816-002 9.8818-001 3.7683-001 4.6331+005  .0000
   LOCATIONS   471 THRU   600 CONTAIN   .000000
```

O2/CH4 DEFAULT ENGINE BALANCE

ENGINE DESCRIPTION	(UNITS)		
TYPE		BELL	
TURBINE DRIVE CYCLE		STAGED COMBUSTION	
PROPELLANTS		O2/CH4	
TURBINE ARRANGEMENT		PARALLEL	
THRUST			
VACUUM	(LBS)	500000.00	
SEA LEVEL	(LBS)	463308.00	
MIXTURE RATIO			
ENGINE	(NONE)	3.500	
THRUST CHAMBER	(NONE)	3.500	
COOLANT BYPASS - ACTUAL	(PERCENT)	10.02	
COOLANT JACKET BYPASS	(PERCENT)	.00	
DELIVERED SPECIFIC IMPULSE			
VACUUM	(SEC)	357.19	
SEA LEVEL	(SEC)	330.98	
		OXIDIZER	FUEL
INLET PROPELLANT PRESSURE	(PSIA)	30.00	30.00
INLET NPSH	(FT)	30.93	83.52
PROPELLANT FLOWRATE	(LBS/SEC)	1088.75	311.07

COMBUSTOR AND NOZZLE DESCRIPTION			
CHAMBER PRESSURE	(PSIA)	3664.26	
AREA RATIO	(AE/AT)	35.00	
NOZZLE PERCENT LENGTH	(PERCENT)	90.00	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	-18.98	
DUMP COOLING FLOW	(LB/SEC)	.00	
COOLANT FLOW SPLIT, WC/WT	(FRACTION)	.50	
		NOZZLE	COMBUSTOR
COOLANT FLOWRATE	(LBS/SEC)	154.32	156.76
COOLANT DELTA P	(PSID)	149.60	1496.02
COOLANT EXIT TEMPERATURE	(DEG R)	623.04	747.95
HEAT INPUT	(BTU/SEC)	39741.64	55308.79
COOLING JACKET OUTLET PRESSURE	(PSIA)	12005.94	10659.53

PREBURNER DESCRIPTION		FUEL	OXIDIZER
GAS TEMPERATURE	(DEG R)	2000.00	2000.00
GAS MIXTURE RATIO	(NONE)	.377	.377
GAS MOLECULAR WEIGHT	(GMS/GM-MOLE)	16.143	16.143
GAS PROCESS GAMMA	(NONE)	1.167	1.167
GAS CP	(BTU/LB-DEG R)	.861	.861
GAS FLOWRATE	(LB/SEC)	233.58	151.78
FUEL HEAT OF FORMATION	(KCAL/MOLE)	-17.57	-17.57
FUEL INLET TEMPERATURE	(DEG R)	686.52	686.52
COMBUSTION PRESSURE	(PSIA)	8781.96	8781.96

TURBOPUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	FUEL	KICK PUMP OXIDIZER	FUEL
PUMP					
HORSEPOWER	(HP)	20568.8	46146.3	5390.8	.0
ROTATING SPEED	(RPM)	17097.1	30916.3	17097.1	.0
EFFICIENCY	(NONE)	.846	.824	.440	.000
INLET PRESSURE	(PSIA)	30.00	30.00	4376.32	.00
OUTLET PRESSURE	(PSIA)	4376.32	12340.03	10488.52	.00
FLOWRATE	(LB/SEC)	1088.75	311.07	105.47	.00
	(GPM)	6860.38	5292.59	664.57	.00
INDUCER					
TIP DIAMETER	(IN)	7.45	5.61		
TIP SPEED	(FT/SEC)	555.89	756.72		
INLET FLOW VELOCITY	(FT/SEC)	57.61	78.42		
FLOW COEFFICIENT	(NONE)	.100	.100		
REQUIRED NPSH	(FT)	103.15	191.15		
IMPELLER					
TIP DIAMETER	(IN)	10.35	8.85	10.87	.00
TIP SPEED	(FT/SEC)	772.46	1194.70	811.84	.00
TIP WIDTH	(IN)	.872	.573	.156	.000
HEAD COEFFICIENT	(NONE)	.474	.505	.603	.000
HEAD RISE PER STAGE	(FT)	8786.61	67196.51	12356.55	.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	1560.50	1228.53	376.10	.00
BOOST PUMP					
MINIMUM DELTA P	(PSI)	35.73	19.72		

TURBINE		OXIDIZER	FUEL
HORSEPOWER	(HP)	25959.67	46146.33
FLOWRATE	(LB/SEC)	151.78	233.58
EFFICIENCY	(NONE)	.665	.768
PRESSURE RATIO	(NONE)	2.183	2.183
ADMISSION	(FRACTION)	.990	.988
VELOCITY RATIO	(NONE)	.307	.480
PITCH DIAMETER	(IN)	8.884	7.681
BLADE HEIGHT	(IN)	.468	.832
HUB/TIP RATIO	(NONE)	.900	.805
TIP SPEED	(FT/SEC)	698.17	1149.24
BEARING DN*E-6	(MM*RPM)	1.000	1.798
ANNULUS AREA*N**2*E-10	((IN*RPM)**2)	.381	1.918
INLET PRESSURE	(PSIA)	8738.05	8738.05
OUTLET PRESSURE	(PSIA)	4002.91	4002.91
INLET TEMPERATURE	(DEG R)	2000.00	2000.00
OUTLET TEMPERATURE	(DEG R)	1858.24	1836.73

PERFORMANCE

THRUST(LBS)	500000.00
CHAMBER PRESSURE(PSIA)	3664.26
ENGINE MIXTURE RATIO	3.50
AREA RATIO	35.00
ODE SPECIFIC IMPULSE(SEC)	370.72
ODE CHARACTERISTIC VELOCITY(FT/SEC)	6130.50
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	.9800
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	1.0000
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	.9952
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	.9882
EFFECTIVE TDK SPECIFIC IMPULSE(SEC)	361.57
BOUNDARY LAYER IS LOSS(SEC)	4.38
DELIVERED SPECIFIC IMPULSE(SEC)	357.19

(INCLUDES EFFECT OF LEAKAGE AND DUMP COOLING FLOWS)

SEA LEVEL SPECIFIC IMPULSE(SEC)	330.98

(VACUUM ISP MINUS AMBIENT PRESSURE DRAG EFFECT)

O2/CH4 GAS GENERATOR CYCLE

STEADY STATE DESIGN AND ENGINE BALANCE PROGRAM

DESIGN OPTIONS IN EFFECT:

		OXIDIZER	FUEL
MAIN TURBOPUMP-			
NUMBER OF CENTRIFUGAL STAGES		1.	2.
TURBINE TYPE FLAG	(1.=1 ROW 2.=2 ROW 3.=50% REACTION 4.=2 STAGE)	2.	2.
TURBINE SIZE FLAG	(0.=2 INCH DIA. 1.=3+ INCH DIA.)	1.	1.
KICK PUMP FLAG-	(0.=NO +.=YES-NO. OF STAGES-)	0.	0.
SCHEMATIC FLAG-		301.	
MINIMIZATION OBJECTIVE FLAG-	(0.=COOLANT PUMP PD 1.=SECONDARY FLOW -2.=P(C))	1.	
INITIAL GUESS CHECK FLAG-	(0.=FULL OPTIMIZATION 1.=1 ITERATION ONLY)	0.	
OXIDIZER TYPE FLAG	(1.=DOUBLE ENTRY 0.=SINGLE ENTRY)	0.	

```
                            ( A )                                 (    B    )
(   C   ) (   D   ) (   E   ) (   F   ) (   G   ) (   H   )

 A = NUMBER OF SUCCESSFUL ITERATIONS
 B = PARAMETER CURRENTLY BEING MINIMIZED:
          FOR D(11)=1.0 - TOTAL TURBINE FLOW RATE
          FOR D(11)=0.0 - MAIN FUEL PUMP DISCHARGE PRESSURE
         (FOR D(11)=0.0 FLOW RATE IS MINIMIZED FIRST THEN PD IS MINIMIZED)
 C = MAIN FUEL PUMP SPEED
 D = MAIN OXIDIZER PUMP SPEED
 E = MAIN FUEL TURBINE ADMISSION
 F = MAIN OXIDIZER TURBINE ADMISSION
 G = COOLANT FLOW SPLIT:  W(COMB)/W(TOTAL)
 H = MAIN FUEL TURBINE PRESSURE RATIO


NO. OF SUCCESSFUL ITERATIONS=   1     PARAMETER BEING MINIMIZED=  .102260+003
 .150000+005  .600000+004  .999000+000  .999000+000  .500000+000  .150000+002

NO. OF SUCCESSFUL ITERATIONS=  10     PARAMETER BEING MINIMIZED=  .693899+002
 .145703+005  .142379+005  .980129+000  .931422+000  .500000+000  .263858+002

NO. OF SUCCESSFUL ITERATIONS=  20     PARAMETER BEING MINIMIZED=  .698164+002
 .143934+005  .117889+005  .982970+000  .942800+000  .500000+000  .300000+002

NO. OF SUCCESSFUL ITERATIONS=  30     PARAMETER BEING MINIMIZED=  .660417+002
 .158894+005  .175889+005  .955683+000  .933400+000  .499589+000  .300000+002

NO. OF SUCCESSFUL ITERATIONS=  40     PARAMETER BEING MINIMIZED=  .644849+002
 .197540+005  .158614+005  .966358+000  .966365+000  .500929+000  .299030+002

NO. OF SUCCESSFUL ITERATIONS=  50     PARAMETER BEING MINIMIZED=  .645858+002
 .193139+005  .161812+005  .974467+000  .965016+000  .500668+000  .298397+002

NO. OF SUCCESSFUL ITERATIONS=  60     PARAMETER BEING MINIMIZED=  .642215+002
 .203730+005  .179657+005  .975455+000  .948811+000  .500583+000  .299253+002

NO. OF SUCCESSFUL ITERATIONS=  70     PARAMETER BEING MINIMIZED=  .641520+002
 .211574+005  .164380+005  .981570+000  .978921+000  .501263+000  .297064+002

NO. OF SUCCESSFUL ITERATIONS=  80     PARAMETER BEING MINIMIZED=  .640752+002
 .211085+005  .179021+005  .967929+000  .940987+000  .500995+000  .300000+002

NO. OF SUCCESSFUL ITERATIONS=  90     PARAMETER BEING MINIMIZED=  .640773+002
 .211319+005  .181994+005  .969067+000  .948755+000  .502406+000  .299503+002

NO. OF SUCCESSFUL ITERATIONS= 100     PARAMETER BEING MINIMIZED=  .640383+002
 .213960+005  .172895+005  .978816+000  .960515+000  .502131+000  .298349+002

NO. OF SUCCESSFUL ITERATIONS= 110     PARAMETER BEING MINIMIZED=  .640187+002
 .213944+005  .174673+005  .983818+000  .954880+000  .502814+000  .298628+002
```

NO. OF SUCCESSFUL ITERATIONS= 120 PARAMETER BEING MINIMIZED= .640251+002
.214894+005 .165685+005 .989018+000 .964185+000 .501347+000 .298317+002

NO. OF SUCCESSFUL ITERATIONS= 130 PARAMETER BEING MINIMIZED= .639625+002
.215279+005 .172157+005 .992757+000 .954451+000 .498469+000 .298973+002

NO. OF SUCCESSFUL ITERATIONS= 140 PARAMETER BEING MINIMIZED= .639671+002
.215902+005 .179372+005 .999999+000 .952112+000 .499136+000 .298174+002

NO. OF SUCCESSFUL ITERATIONS= 150 PARAMETER BEING MINIMIZED= .639174+002
.216647+005 .174822+005 .999999+000 .935386+000 .499616+000 .299807+002

NO. OF SUCCESSFUL ITERATIONS= 160 PARAMETER BEING MINIMIZED= .639391+002
.216019+005 .178474+005 .996755+000 .934701+000 .496080+000 .299737+002

NO. OF SUCCESSFUL ITERATIONS= 170 PARAMETER BEING MINIMIZED= .639255+002
.216650+005 .168870+005 .998450+000 .950368+000 .497732+000 .299432+002

```
COMMON-BLOCK /A/

  1 5.0000+005 3.5000+001 3.5000+003 3.5000+000 1.0000-001 2.0000+000 3.0100+002  .0000      .0000      .0000
 11 1.0000+000  .0000     2.0000+003 1.4000+003 5.0000+003  .0000     3.0000-002 3.0000-002 1.0000+000 1.0000+000
 21 1.8000+006 1.0000+006 8.0000-001 8.0000-001 1.6000+003 1.6000+003 1.6000+003 1.6000+003 1.0000+006  .0000
 31 4.0000+002 4.0000+002 2.2000+003 2.2000+003 2.0000+000 2.0000+000 1.0000+002 1.0000+002  .0000      .0000
   LOCATIONS    41 THRU    70 CONTAIN   .000000
 71  .0000      .0000      .0000      .0000      .0000      .0000     5.0000+003 5.0000+003 9.0000-001 9.0000-001
 81 4.9000-001 5.0000+000  .0000     5.0000+004 5.0000+004 1.0000+000 1.0000+000 5.1000-001 3.0000+001  .0000
 91  .0000      .0000      .0000     1.3000+000 1.0000-004 1.0000+000 1.6000+003 2.5000-001 4.0000+010 2.0000+000
101 2.0000+000 2.0000+000 9.0000-001 1.0000+000 1.0000+000 2.0000+003 2.0000+003 6.0000-001  .0000      .0000
111 3.0000+001 3.0000+001 1.5300+001 1.5300+001  .0000      .0000     2.0000+000 1.0000+000  .0000      .0000
121 1.0000-001 1.0000-001  .0000      .0000     3.5000-001 3.5000-001  .0000      .0000      .0000      .0000
131 5.0000-003 1.0000-002 5.0000-002 1.0000-001 1.5000-001 8.0000-002  .0000      .0000      .0000     3.0000+001
141 1.6147+002 1.6399+002 1.3314+003 1.3314+002 2.0000-001 1.0000+002  .0000      .0000      .0000      .0000
151 1.5000+004 6.0000+003 9.9900-001 9.9900-001 5.0000-001 1.5000+001 1.4153+003 1.4258+003 6.6326+002 5.7470+002
161  .0000      .0000     1.0000-004 2.0000+003 2.0000+003 9.8000-001  .0000     1.1390+000 6.0211+002  .0000
171 5.1125+002 4.1178+002 4.6113+002  .0000      .0000      .0000      .0000      .0000      .0000      .0000
   LOCATIONS   181 THRU   190 CONTAIN   .000000
191 9.0000-001 9.8200-001  .0000      .0000     4.5631-002 3.2546+002 1.1391+003 4.5975+001 1.7939+001 7.2804+001
201 1.9313+000 4.9211+005 4.0116+000 3.5135+002 1.2337+002 2.6380+001 7.1230+001 1.6043+001 3.1999+001-2.1390+001
211-3.1020+000 2.0000+000 2.0000+000 1.2331+002  .0000      .0000      .0000      .0000      .0000      .0000
221 3.0000+001 3.0931+001 2.6975+001 3.0000+001 4.1801+003 4.1592+003 4.1176+003 3.0000+001 8.3518+001 2.9973+001
231 3.0000+001 5.2137+003 5.1357+003 3.8043+003 3.7853+003 5.0026+003  .0000      .0000      .0000     9.0369+002
241 3.1342+003 3.0000+001 3.0000+001 3.8043+003 3.5000+003  .0000      .0000      .0000     1.0938+001 1.3888+001
251 5.5521+004 4.0076+004 5.3566+002 6.6573+002 5.8730+001 5.6670+002 1.0000-001  .0000     7.5428+000 3.9210+001
261  .0000      .0000      .0000      .0000     1.0721+002  .0000     7.6221+002  .0000     4.6464-001 1.0145+001
271 9.1314-001 7.4349-001 1.6629+003 8.3900+003  .0000     8.4834-001 2.0481+004  .0000     6.2780+001 6.0578+002
281 1.0000-001  .0000     6.4078+000 2.8298+001  .0000      .0000      .0000      .0000     1.2250+002  .0000
291 9.5073+002  .0000     5.0360-001 1.0057+001 6.5926-001 6.3718-001 1.2420+003 2.8296+004  .0000     8.2493-001
301 2.0296+004  .0000     3.9018-001 1.6246+001 1.1892+000 7.7821-001  .0000      .0000      .0000     1.1892+000
311 7.7821-001 2.0000+003 2.0000+003  .0000     1.6246+001 3.9018-001  .0000     7.0381-001 1.9765+001 3.2393+001
321 2.0481+004 1.5310+000 3.9665+000 2.6532-001 1.6000+003 2.8141+010 4.0000+000 9.2777+005 6.9987-001 1.5131+001
331 3.1520+001 2.0296+004 1.7934+000 4.4655+000 2.5255-001 1.6000+003 3.9955+010 3.0000+000 1.0781+006 3.7730+001
341 7.1416+000 7.1776+003 5.5373+003 8.5622-001 7.8807-001  .0000      .0000      .0000      .0000      .0000
   LOCATIONS   351 THRU   360 CONTAIN   .000000
361  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     2.1649+004  .0000
371  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     1.7205+004  .0000
381  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     9.9723-001  .0000
391  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     9.4578-001  .0000
401  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     4.9612-001  .0000
411  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     2.9973+001  .0000
421  .0000      .0000      .0000      .0000      .0000      .0000      .0000      .0000     2.7948+002 1.1212+003
431 3.4968+002 6.3913+001  .0000      .0000     9.3550+001  .0000     3.4400+002  .0000     6.3913+001  .0000
   LOCATIONS   441 THRU   450 CONTAIN   .000000
451  .0000      .0000    -1.8335+001-1.8335+001 3.4140+002 5.8533+003 3.1467+002 3.6469+002 5.9728+003 3.9018-001
461 3.9018-001-1.9076+001 1.0000+000 9.8000-001 9.9521-001 1.1886-002 9.8811-001 3.9018-001 4.6084+005  .0000
   LOCATIONS   471 THRU   600 CONTAIN   .000000
```

O2/CH4 GAS GENERATOR CYCLE

ENGINE DESCRIPTION	(UNITS)		
TYPE		BELL	
TURBINE DRIVE CYCLE		GAS GENERATOR	
PROPELLANTS		O2/CH4	
TURBINE ARRANGEMENT		PARALLEL	
THRUST			
VACUUM	(LBS)	500000.00	
SEA LEVEL	(LBS)	460843.57	
MIXTURE RATIO			
ENGINE	(NONE)	3.500	
THRUST CHAMBER	(NONE)	4.012	
COOLANT BYPASS - ACTUAL	(PERCENT)	83.55	
COOLANT JACKET BYPASS	(PERCENT)	.00	
DELIVERED SPECIFIC IMPULSE			
VACUUM	(SEC)	341.40	
SEA LEVEL	(SEC)	314.67	
		OXIDIZER	FUEL
INLET PROPELLANT PRESSURE	(PSIA)	30.00	30.00
INLET NPSH	(FT)	30.93	83.52
PROPELLANT FLOWRATE	(LBS/SEC)	1139.10	325.46

COMBUSTOR AND NOZZLE DESCRIPTION			
CHAMBER PRESSURE	(PSIA)	3500.00	
AREA RATIO	(AE/AT)	35.00	
NOZZLE PERCENT LENGTH	(PERCENT)	90.00	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	-19.08	
DUMP COOLING FLOW	(LB/SEC)	.00	
COOLANT FLOW SPLIT, WC/WT	(FRACTION)	.50	
		NOZZLE	COMBUSTOR
COOLANT FLOWRATE	(LBS/SEC)	163.99	161.47
COOLANT DELTA P	(PSID)	133.14	1331.36
COOLANT EXIT TEMPERATURE	(DEG R)	535.66	665.73
HEAT INPUT	(BTU/SEC)	40075.51	55520.71
COOLING JACKET OUTLET PRESSURE	(PSIA)	5002.58	3804.35

GG GAS PROPERTIES		FUEL	OXIDIZER
GAS TEMPERATURE	(DEG R)	2000.00	2000.00
GAS MIXTURE RATIO	(NONE)	.390	.390
GAS MOLECULAR WEIGHT	(GMS/GM-MOLE)	16.246	16.246
GAS PROCESS GAMMA	(NONE)	1.189	1.189
GAS CP	(BTU/LB-DEG R)	.778	.778
GAS FLOWRATE	(LB/SEC)	31.52	32.39
FUEL HEAT OF FORMATION	(KCAL/MOLE)	-18.33	
FUEL INLET TEMPERATURE	(DEG R)	602.11	
COMBUSTION PRESSURE	(PSIA)	903.69	

TURBOPUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	KICK PUMP OXIDIZER	KICK PUMP FUEL
PUMP					
HORSEPOWER	(HP)	20481.4	20295.9	.0	.0
ROTATING SPEED	(RPM)	17205.2	21649.2	.0	.0
EFFICIENCY	(NONE)	.848	.825	.000	.000
INLET PRESSURE	(PSIA)	30.00	30.00	.00	.00
OUTLET PRESSURE	(PSIA)	4180.14	5213.66	.00	.00
FLOWRATE	(LB/SEC)	1139.10	325.46	.00	.00
	(GPM)	7177.60	5537.31	.00	.00
INDUCER					
TIP DIAMETER	(IN)	7.54	6.41		
TIP SPEED	(FT/SEC)	566.70	605.78		
INLET FLOW VELOCITY	(FT/SEC)	58.73	62.78		
FLOW COEFFICIENT	(NONE)	.100	.100		
REQUIRED NPSH	(FT)	107.21	122.50		
IMPELLER					
TIP DIAMETER	(IN)	10.15	10.06	.00	.00
TIP SPEED	(FT/SEC)	762.21	950.73	.00	.00
TIP WIDTH	(IN)	.913	.659	.000	.000
HEAD COEFFICIENT	(NONE)	.465	.504	.000	.000
HEAD RISE PER STAGE	(FT)	8390.01	28295.92	.00	.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	1662.88	1241.95	.00	.00
BOOST PUMP					
MINIMUM DELTA P	(PSI)	37.73	7.14		

TURBINE		OXIDIZER	FUEL
HORSEPOWER	(HP)	20481.42	20295.87
FLOWRATE	(LB/SEC)	32.39	31.52
EFFICIENCY	(NONE)	.704	.700
PRESSURE RATIO	(NONE)	26.975	29.973
ADMISSION	(FRACTION)	.946	.997
VELOCITY RATIO	(NONE)	.265	.253
PITCH DIAMETER	(IN)	19.765	15.131
BLADE HEIGHT	(IN)	1.531	1.793
HUB/TIP RATIO	(NONE)	.856	.788
TIP SPEED	(FT/SEC)	1600.00	1600.00
BEARING DN*E-6	(MM*RPM)	.928	1.078
ANNULUS AREA*N**2*E-10	((IN*RPM)**2)	2.814	3.996
INLET PRESSURE	(PSIA)	809.26	899.18
OUTLET PRESSURE	(PSIA)	30.00	30.00
INLET TEMPERATURE	(DEG R)	2000.00	2000.00
OUTLET TEMPERATURE	(DEG R)	1425.81	1415.25

```
PERFORMANCE

        THRUST(LBS)                                       500000.00
        CHAMBER PRESSURE(PSIA)                              3500.00
        ENGINE MIXTURE RATIO                                   3.50
        AREA RATIO                                            35.00

        ODE SPECIFIC IMPULSE(SEC)                            364.69
        ODE CHARACTERISTIC VELOCITY(FT/SEC)                 5972.80

        SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY             .9800
        SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY          1.0000
        SPECIFIC IMPULSE DIVERGENCE EFFICIENCY                 .9952
        SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY             .9881

        EFFECTIVE TDK SPECIFIC IMPULSE(SEC)     355.69
        BOUNDARY LAYER IS LOSS(SEC)               4.33

        DELIVERED SPECIFIC IMPULSE(SEC)         341.40
        (INCLUDES EFFECT OF LEAKAGE AND DUMP COOLING FLOWS)

        SEA LEVEL SPECIFIC IMPULSE(SEC)         314.67
        (VACUUM ISP MINUS AMBIENT PRESSURE DRAG EFFECT)

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```

CODE STRUCTURE

This section provides an overall description of the code structure including subroutine interactions, common blocks, iteration loops, and propellant- and cycle-dependent coding. The program is modularized for the most part, with each subroutine relatively limited in scope. This approach is designed to facilitate modifications and additions, when required.

PROGRAM LOGIC

The program consists of a main program and 30 subprograms. The main program, AMAIN, controls input/output and calls MAIND, which contains the engine balance and optimization logic. A block diagram of the program is included in Fig. 16, which shows subroutine interactions with brief descriptions of the purpose of each subroutine call. A cross-reference list of subroutine calls is shown in Table 2.

A flow chart of the balance and optimization process is shown in Fig. 17. An engine balance is performed for a given set of conditions without regard to implicit constraints. When a balance is achieved, control passes to the optimizer, which checks for constraint violation. The optimizer independent variables are then varied and another balance is performed.

COMMON BLOCKS

Several common blocks are used to pass data efficiently among subroutines. Common block A is of most interest to the user and contains user inputs and calculated variables. The other common blocks contain propellant performance, kinetic efficiency, and turbine drive gas property data. Table 3 describes the common block characteristics. Common Block A is described in detail in the Common Block description section and the format of the common blocks is described in the User Instructions section.

ITERATION LOOPS

Several iteration loops are required in the program due to the non-linear nature of the calculations. There are four iterations which use subroutines

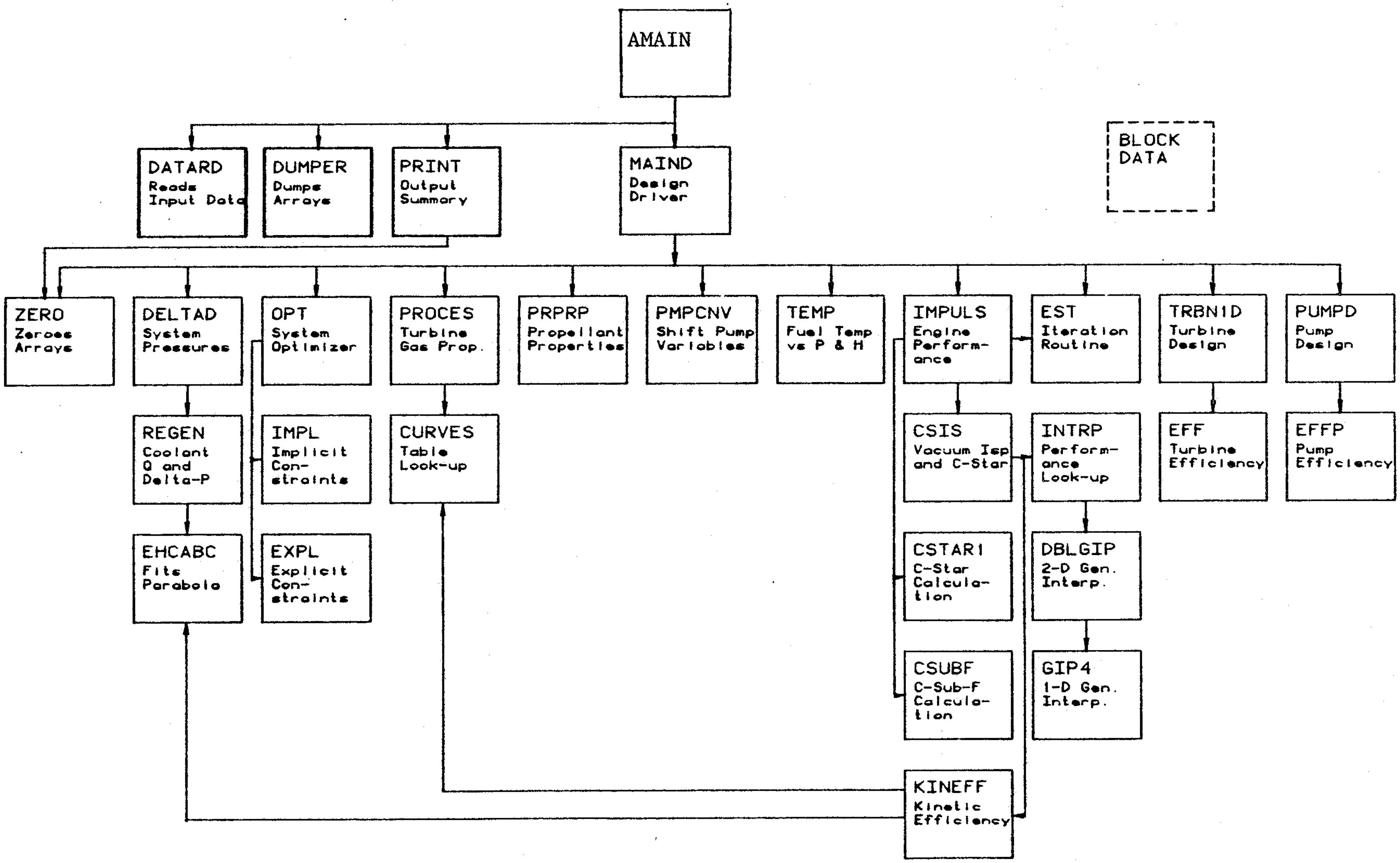

FIGURE 16. BALANCE PROGRAM BLOCK DIAGRAM

TABLE 2 : SUBROUTINE REFERENCES

NAME	SUBROUTINES CALLED	CALLED BY
AMAIN	DATARD, ZERO, MAIND, DUMPER, PRINT	-----
BDATA	------------------	-----
CSIS	INTRP, KINEFF	IMPULS
CSTAR1	------------------	IMPULS
CSUBF	------------------	IMPULS
CURVES	------------------	KINEFF, PROCES
DATARD	------------------	AMAIN
DBLGIP	GIP4	INTRP
DELTAD	REGEN	MAIND
DUMPER	------------------	AMAIN
EFF	------------------	TRBNID
EFFP	------------------	PUMPD
EHCABC	------------------	KINEFF, REGEN
EST	------------------	IMPULS, MAIND
EXPL	------------------	OPT
EXPST (ENTRY IN DELTAD)	------------------	MAIND
GIP4	------------------	INTRP, DBLGIP
IMPL	------------------	OPT
IMPULS	EST, CSIS, CSTAR1, CSUBF	MAIND
INTRP	GIP4, DBLGIP	CSIS
KINEFF	CURVES, EHCABC	CSIS
MAIND	PRPRP, PROCES, IMPULS	AMAIN
MAIND	DELTAD, TEMP, ZERO	AMAIN
MAIND	PUMPD, PMPCNV, TRBNID	AMAIN
MAIND	EST, EXPST, OPT	AMAIN
OPT	EXPL, IMPL	MAIND
PMPCNV	------------------	MAIND
PRINT	ZERO	AMAIN
PROCESS	CURVES	MAIND
PUMPD	EFFP	MAIND
PRPRP	------------------	MAIND
REGEN	EHCABC	DELTAD
TEMP	------------------	MAIND
TRBN1D	EFF	MAIND
ZERO	------------------	AMAIN, MAIND, PRINT

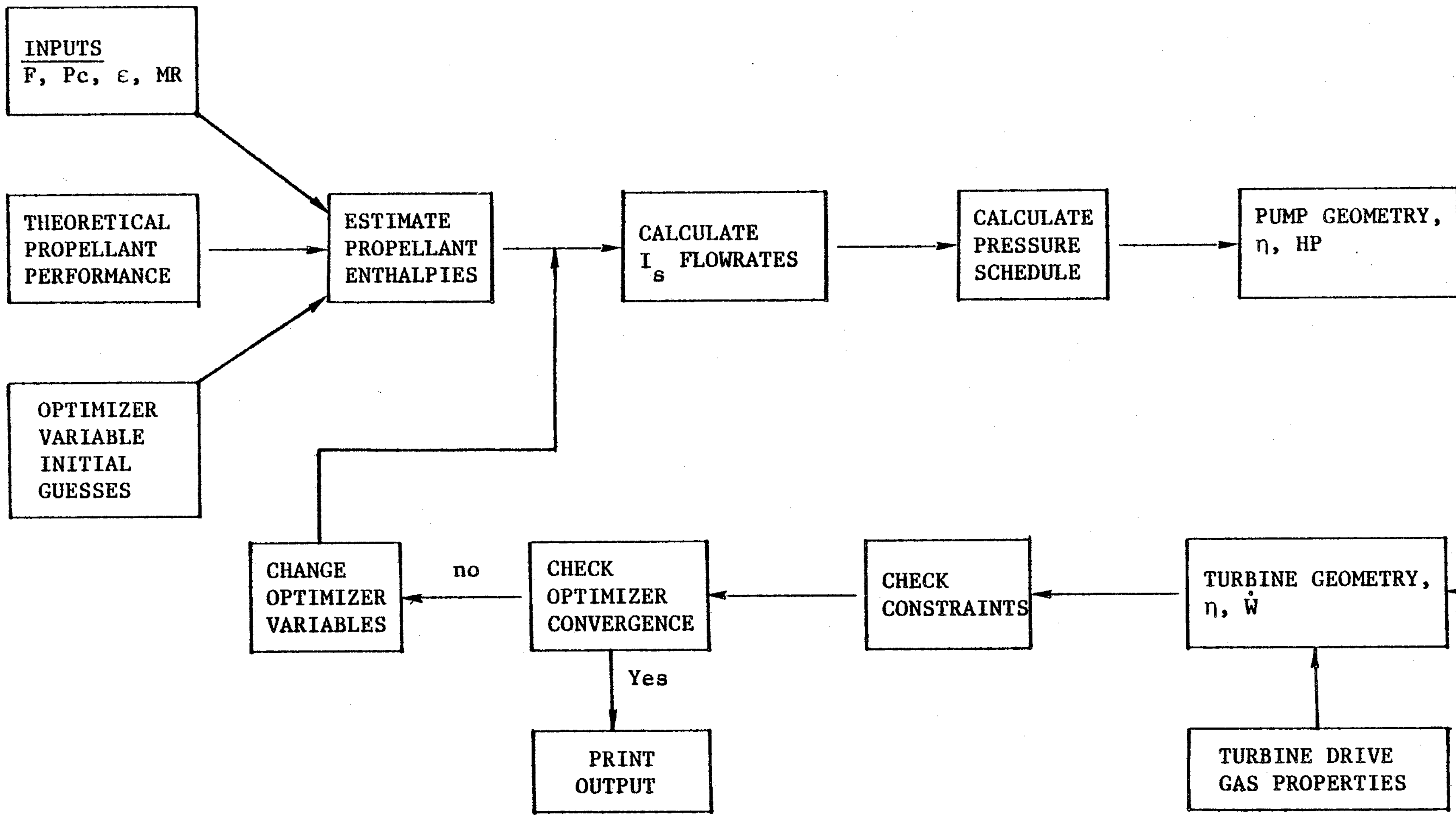

FIGURE 17. BALANCE PROGRAM FLOW CHART

TABLE 3 : COMMON BLOCK DESCRIPTION

NAME OF COMMON BLOCK	SIZE IN REAL VARIABLES	DESCRIPTION	REFERENCED BY
A	600	Contains input/output design data array, partially read in from logical file unit no. 5.	AMAIN, BDATA, DELTAD. IMPL, IMPULS, MAIND, PROCES, PRPRP, REGEN
TABSIZ	5	Contains dimension data for propellant performance data array contained in common block IS.	AMAIN, INTRP
EFFK	3081	Contains kinetic efficiency read from logical file unit no. 4.	AMAIN, KINEFF
IS	4010	Contains propellant performance data array read from logical file unit no. 3.	AMAIN, CSIS, IMPULS
GGDATA	5143	Contains turbine drive gas property tables.	BDATA, PROCES

EST and three which are coded inline. Subroutine EST uses a Newton-Raphson technique and can handle nested loops. Table 4 summarizes the location and purpose of the EST loops.

Inline iterations occur in MAIND, PUMPD, and TRBN1D. An initial estimate of specific impulse is necessary in MAIND to calculate propellant flowrates. The actual specific impulse is calculated at the end of the balance and resubstituted until the old and new values match to the required tolerance. In PUMPD and TRBN1D, the pump and turbine efficiencies must be estimated before the required geometry and operating parameters can be calculated which are needed to determine the actual efficiency. Resubstitution is used in PUMPD and the method of false position in TRBN1D.

PROPELLANT- AND CYCLE-DEPENDENT CODING

Most of the subroutines that contain calculations or data which depend on the propellant combination or schematic configuration have been written to minimize the effort required to incorporate modifications or additions. This was done primarily by concentrating particular types of data or calculations in a single subroutine. Nevertheless, it is recommended that care be taken to insure that a subroutine's functions and interactions are well understood before changes are made. Tables 5 and 6 show the location and a brief description of the propellant-dependent and cycle-dependent coding, respectively. Further information is included in the subroutine descriptions.

TABLE 4. ITERATION LOOP DESCRIPTION

LOOP I.D.	VARIABLE CHANGED BY EST	VARIABLES CONVERGED	LOCATION
1	Nozzle Exit Mach. No.	Calculated area ratio, actual area ratio	IMPULS
2	Thrust Chamber mixture ratio (Sc and expander cycles)	Calculated engine mixture ratio, actual engine mixture ratio	IMPULS
3	Thrust Chamber mixture ratio (GG cycle)	Calculated engine mixture ratio, actual engine mixture ratio	IMPULS
4	Oxidizer Turbine pressure ratio (Expander cycle with series turbines)	Required turbine flowrate, available turbine flowrate	MAIND

TABLE 5. PROPELLANT-DEPENDENT SUBROUTINE DESCRIPTION

SUBROUTINE	DESCRIPTION
BLOCK DATA:	Tables of turbine drive gas properties
DELTAD:	Valve and injector pressure drops are set depending on whether fuel is liquid or gas
PRINT:	Propellant names are printed
PROCES:	Turbine drive gas properties are calculated
PRPRP:	Propellant physical properties are initialized
REGEN:	Coolant heat loads and delta P's are calculated
TEMP:	Calculates fuel temperatures as a function of pressure and enthalpy

TABLE 6. CYCLE-DEPENDENT SUBROUTINE DESCRIPTION

SUBROUTINE	DESCRIPTION
DELTAD:	Calculates pressure schedule
IMPL:	Checks for implicit constraint violation
IMPULS:	Calculates performance
MAIND:	Turbine and pump inputs and object function may depend on schematic
PRINT:	Cycle name and turbine drive gas properties are printed
PROCES:	Turbine drive gas properties are calculated

SUBROUTINE DESCRIPTIONS

Each subroutine is described to indicate its purpose, how it is used, inputs and outputs, common blocks referenced, subroutines called, and the methods used by the routine.

MAIN PROGRAM (AMAIN)

Purpose:	Controls program input and output, prints summary of user-selected options, and calls MAIND, which controls engine balance calculations.
Input/Output Files:	3 - Theoretical propellant performance data 4 - Kinetic efficiency data 5 - User - specified inputs 6 - Output
Subprograms Used:	DATARD, ZERØ, MAIND, DUMPER, PRINT
Common Blocks Used:	A, TABSIZ, EFFK, IS

SUBROUTINE BDATA (BLOCK DATA)

PURPOSE: To fill turbine drive gas property tables and to initialize common block A with default inputs.

USE: BLOCK DATA subroutine.

INPUTS: None

OUTPUTS: Turbine drive gas property tables and common block A default values.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: A, GGDATA

CALLED BY: Not applicable. Initialization is performed upon program execution.

METHOD: Block data subroutine.

RESTRICTIONS: The data provided are applicable over the following ranges:

FLUID	TABLE	ARRAY NAME	APPLICABLE RANGE
Fuel-rich	Cp(Hf,MR,PR)	CTBL	Hf:-21.355 to -17.488
O_2/CH_4	Gamma(Hf,MR,PR)	GTBL	MR: 0.2 to 1.5
			PR: 1.10 to 100
Fuel-rich	Cp(Hf,P,MR,PR)	CP1,CP2	Hf:-2.154 to 0
O_2/H_2	Gamma(Hf,MR,PR)	GA1,GA2	P: 5000 to 15000 psia
			MR: 0.7 to 2.0
			PR: 1.10 to 100
H_2 gas	Cp(P,PR,T)	H2CP	P: 500 to 2000 psia
	Gamma(P,PR,T)	H2GAM	PR: 1.05 to 3.0
			T: 200 to 1000 Rankine
Oxid-rich	Cp(PR,MR)	RPCP	PR: 1.0 to 2.0
O_2/RP-1	Gamma(PR,MR)	RPGAM	MR: 27 to 53
CH_4 gas	Cp(P,PR,T)	CH4CP	P: 300 to 3000 psia
	Gamma(P,PR,T)	CH4GAM	PR: 1.05 to 3.0
			T: 500 to 900 Rankine
Fuel-rich	Cp(Hf,PR,MR)	C3H8CP	Hf: -32.2 to -24.83
O_2/C_3H_8	Gamma(Hf,PR,MR)	C3H8GM	PR: 1.10 to 100
	MR(Hf,T)	C3H8MR	MR: 0.2 to 1.2
	MW(Hf,MR)	C3H8MW	

(Hf, heat of formation, in units of Kcal/gm-mole)

SUBROUTINE CSIS

Purpose: Calculates thrust chamber specific impulse and C star for a bell nozzle.

Use: Call CSIS (F, PC, MR, EPS, PCTLNG, HF, ISACT, CSTAR, ISTHEØ, EFFTDK, ETAK)

Inputs:	F	Vacuum thrust, lb
	PC	Chamber pressure, psia
	MR	Thrust chamber mixture ratio
	EPS	Nozzle area ratio
	PCTLNG	Nozzle percent length
	HF	Thrust chamber fuel inlet heat of formation, Kcal/g-mole
	ETAK	Kinetic efficiency; if equal to 0.0, efficiency is supplied by KINEFF
	P(4010)	Theoretical specific impulse and C-star data
	EFFTDK (2)	C-star efficiency
Outputs:	ISACT	Delivered thrust chamber specific impulse, sec
	CSTAR	Delivered thrust chamber c-star, ft/sec
	ISTHEØ	Theoretical thrust chamber specific impulse, sec
	CSTHEO	Theoretical thrust chamber c-star, ft/sec
	EFFTDK (1)	Kinetic efficiency, η_k
	EFFTDK (3)	Divergence efficiency, η_{div}
	EFFTDK (4)	Boundary layer loss, $1 - \eta_{BL}$
	EFFTDK (5)	Boundary layer efficiency, η_{BL}

Subprograms used: INTRP, KINEFF

Common blocks used: IS

Called by: IMPULS

Method: The simplified JANNAF methodology is used to calculate delivered thrust chamber performance. Theoretical specific impulse and C-star are provided by INTRP, which interpolates in the input table. Divergence and boundary layer efficiencies are calculated with curve-fits of data generated by nozzle analysis programs. Kinetic efficiency can be input by the user or interpolated by KINEFF if a table is input. C-star efficiency is a user input. Performance is calculated with the following equations:

$$C^*_{delivered} = \eta_{C^*} \times C^*_{theoretical}$$

$$\eta_{I_S} = \eta_{C^*} \times \eta_{div} \times \eta_K - (1 - \eta_{BL})$$

$$I_{S\ delivered} = \eta_{I_S} \times I_{S\ theoretical}$$

Restrictions: The curve-fit for boundary layer loss (DELBL) is for a regeneratively cooled thrust chamber. For an ablative thrust chamber the leading constant should be changed from .0067574 to .0042444.

It should also be noted that for area ratios below about 3-6, a 15-degree cone will provide higher performance than a bell nozzle.

SUBROUTINE CSTAR1

PURPOSE: To compute turbine exhaust characteristic velocity, C*.

USE: CALL CSTAR1 (G,AM,T,ANS)

INPUTS: G : Gas isentropic exponent, γ.

AM : Gas molecular weight, gram/g-mole.

T : Gas temperature, Deg-R.

OUTPUTS: ANS : Characteristic velocity, ft/sec.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: IMPULS

METHOD: Characteristic velocity is computed as follows.

$$C^* = \frac{\left(g\ \gamma\ R\ T\right)^{.5}}{\gamma\ \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}}$$

SUBROUTINE CSUBF

PURPOSE: To compute thrust coefficient for turbine exhaust gas.

USE: CALL CSUBF (G,P1,P2,CFOPT,CFVAC)

INPUTS: G : Gas isentropic exponent, γ.

P1 : Gas stagnation pressure, psia.

P2 : Exit static pressure, psia.

OUTPUTS: CFOPT : Thrust coefficient in atmosphere,ie. PA = P2.

CFVAC : Thrust coefficient in vacuum.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: IMPULS

METHOD: Thrust coefficient is computed as follows.

$$CFOPT = \left\{ \left(\frac{2\gamma^2}{\gamma-1}\right) \left(\frac{2}{\gamma+1}\right)^{2\alpha} \left[1 - \left(\frac{P2}{P1}\right)^{\varepsilon}\right] \right\}^{.5}$$

$$CFVAC = CFOPT + \left(\frac{P2}{P1}\right) \frac{\left[\frac{2}{\gamma+1} \left(\frac{P1}{P2}\right)^{\varepsilon}\right]^{\alpha}}{\left\{\frac{2}{\gamma-1} \left[\left(\frac{P1}{P2}\right)^{\varepsilon} - 1\right]\right\}^{.5}}$$

where:

$$\alpha = \frac{\gamma+1}{2(\gamma-1)}$$

$$\varepsilon = \frac{\gamma-1}{\gamma}$$

SUBROUTINE CURVES

PURPOSE: To obtain the value of a single dependent variable as a function of from one to three independent variables by interpolation or extrapolation within a set of tabular data. In general notation, Z = f(W, X, Y) , where Z is the dependent variable and W, X, and Y are the three independent variables.

USE: CALL CURVES (L,TBL,W,X,Y,Z,KK)

INPUTS:

L : Integer identification used in case of error or extrapolation.

- > 0 : normal interpolation.
- < 0 : causes the tabular "Z" values to be treated as the innermost independent variable, and the "Y" values to become the dependent variable; thus provides exchanging roles in the interpolation. The curve produced by such an exchange must be monotonic.
- = 0 : ID's are printed for CURVES calls requiring extrapolation.

TBL : Data table. Data must be entered in the format described below.

W : First independent variable.

X : Second independent variable.

Y : Third independent variable.

OUTPUTS: Z : Interpolated or extrapolated result (dependent variable).

K : Integer indicator specified as follows.

= 0 : interpolation occurred.

= -1 : extrapolation occurred.

= 1 : numerical error, either first tabular entry is zero or the independent variables are not monotonic. No Z value is returned.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: KINEFF, PROCES

METHOD: Interpolation is obtained by means of a four-point Lagrange type of curve fitting procedure. Linear extrapolation is obtained by using the adjacent two end points.

RESTRICTIONS:

1) The number of entries of each independent variable must be no greater than 99.

2) The number of entries of independent variable Y may not be indicated as zero.

3) The routine will resort to linear interpolation whenever only two entries are available for interpolation.

4) The "size" entry must be in floating point form and be the first entry in the tabular data.

5) The number of Y's under each X must be the same but the values can be different. The same flexibility applies to the list of X's under several W's.

INPUT DATA FORMAT:

The tabular data provided in table named "TBL" must appear in the data vector as shown in Tables A through C. Table A shows the form to be used for three independent variables, Z = f(W,X,Y). Table B shows the form to be used for two independent variables, Z = f(X,Y). Table C shows the form to be used for one independent variable, Z = f(Y).

The "size" entry is the first entry in the data vector which contains the tabular data. This entry indicates the number of entries (Wn) of independent variable W in the table, the number of entries (Xn) of independent variable X which will appear in the table for each W, and the number of entries (Yn) of independent variable Y which will appear in the table for each X. Wn, Xn, and Yn are each limited to a value of no greater than 99. The size entry must be a floating point number and may be computed as follows.

size = 10000.*Wn + 100.*Xn + Yn

The total number of entries in the data table including the size entry may be computed as follows.

Length of Table with 3 Ind. Vars. = [(2*Yn + 1)*Xn + 1]*Wn +1

Length of Table with 2 Ind. Vars. = (2*Yn +1)*Xn + 2

Length of table with 1 Ind. Var. = 2*Yn + 3

Two or more entries must be indicated (by the size entry) for an independent variable for interpolation to take place as a function of that variable. If one or zero entries are indicated, no attempt will be made by the routine to match the value of the argument in the CALL statement with any entries in the table. The only qualification is that the number of Y entries, Yn, may not be indicated as zero. If Yn is zero, the routine will presume the table to be incorrectly written or that it is missing and an error indication to this effect will be printed.

USAGE EXAMPLES:

The following examples illustrate the manner of usage of this subroutine and of tabular data input.

Example 1 :

A program is written considering enthalpy h = f (P, T). The following (abbreviated) table is written in the manner of Table B.

1)	Size 204. or 10204.		11)	h	2319
2)	0. or blank		12)	P	2000
3)	P	1000	13)	T	300
4)	T	300	14)	h	-898
5)	h	-900	15)	T	600
6)	T	600	16)	h	243
7)	h	227	17)	T	900
8)	T	900	18)	h	1296
9)	h	1275	19)	T	1200
10)	T	1200	20)	h	2342

The following CALL statement will return the enthalpy value in H4 at the pressure and temperature specified by P4 and T4, respectively.

```
CALL CURVES (8*, PTHTBL, 0., P4, T4, H4, K)
```

Example 2:

The preceding table may also be used in order to obtain temperature as a function of pressure and enthalpy. The following CALL statement will return the temperature in T5 at the pressure and enthalpy specified by P5 and H5, respectively.

```
CALL CURVES (-12, PTHTBL, 0., P5, H5, T5, K)
```

* The value of 'L' is arbitrary but should not be duplicated within a given program as it is used to identify the calling location if an error occurs.

Example 3:

The program has been written considering C* = f(P, MR). Presume data to be available at only one value of mixture ratio (MR) and at several values of chamber pressure (P). The table might be written as follows.

1)	size	401.	8)	C*	5600
2)	blank		9)	P	500
3)	P	100	10)	MR	blank
4)	MR	blank	11)	C*	5650
5)	C*	5500	12)	P	1000
6)	P	200	13)	MR	blank
7)	MR	blank	14)	C*	5675

Note that the value of MR need not be input in the tabular data, though may be if so desired.

The following CALL statement will return the value of characteristic velocity in CSTAR as a function of chamber pressure specified by PC. The mixture ratio specified by MR is ignored.

```
CALL CURVES (2, CSTBL, 0., PC, MR, CSTAR, K)
```

Example 4:

The program has been written considering PR = f(H, M). Presume that the variation of PR with H is temporarily unknown. The data table might be written as follows.

1)	size	5. or 105.	8)	M	1.0
2)	blank		9)	PR	0.95
3)	H	blank	10)	M	2.0
4)	M	0.	11)	PR	0.85
5)	PR	1.0	12)	M	3.0
6)	M	0.5	13)	PR	0.70
7)	PR	0.98			

Note that no entry needs to be made for H.

Example 5:

The program has been written considering Is = f(P, MR, EPS). Presume that data is unavailable to begin program check-out, and a constant value of Is=300. is to be used. The data table might be written as follows.

1)	size	1. or 10101.
2)	P	blank
3)	MR	blank
4)	EPS	blank
5)	Is	300.

The following CALL statement will always return a value of 300. in the variable named SI regardless of the values specified by P, EMR and EPS.

```
CALL CURVES (2, SITBL, P, EMR, EPS, SI, K)
```

Example 6:

The following call may be placed at the end of the program in order to obtain a listing of the calls which required extrapolation. All arguments excepts the first are dummies and are not used.

```
CALL CURVES (0, D, D, D, D, D, K)
```

CURVES SUBROUTINE

Order of Data Input

- TABLE A : Z = f(W, X, Y) -

```
  1)  40304. (size*)
  2)  W1
  3)    X1
  4)      Y1
  5)        Z
  6)      Y2
  7)        Z
  8)      Y3
  9)        Z
 10)      Y4
 11)        Z
 12)    X2
 13)      Y1
 14)        Z
 15)      Y2
 16)        Z
 17)      Y3
 18)        Z
 19)      Y4
 20)        Z
 21)    X3
 22)      Y1
 23)        Z
 24)      Y2
 25)        Z
 26)      Y3
 27)        Z
 28)      Y4
 29)        Z
 30)  W2
 31)    X1
 32)      Y1
 33)        Z
 34)      Y2
 35)        Z
 36)      Y3
 37)        Z
 38)      Y4
 39)        Z
 40)    X2
 41)      Y1
 42)        Z
 43)      Y2
 44)        Z
 45)      Y3
 46)        Z
 47)      Y4
 48)        Z
 49)    X3
 50)      Y1
 51)        Z
 52)      Y2
 53)        Z
 54)      Y3
 55)        Z
 56)      Y4
 57)        Z
 58)  W3
 59)    X1
 60)      Y1
 61)        Z
 62)      Y2
 63)        Z
 64)      Y3
 65)        Z
 66)      Y4
 67)        Z
 68)    X2
 69)      Y1
 70)        Z
 71)      Y2
 72)        Z
 73)      Y3
 74)        Z
 75)      Y4
 76)        Z
 77)    X3
 78)      Y1
 79)        Z
 80)      Y2
 81)        Z
 82)      Y3
 83)        Z
 84)      Y4
 85)        Z
 86)  W4
 87)    X1
 88)      Y1
 89)        Z
 90)      Y2
 91)        Z
 92)      Y3
 93)        Z
 94)      Y4
 95)        Z
 96)    X2
 97)      Y1
 98)        Z
 99)      Y2
100)        Z
101)      Y3
102)        Z
103)      Y4
104)        Z
105)    X3
106)      Y1
107)        Z
108)      Y2
109)        Z
110)      Y3
111)        Z
112)      Y4
113)        Z
```

* 4 entries for W, 3 entries for X, and 4 entries for Y

CURVES SUBROUTINE

Order of Data Input (Contd.)

- TABLE B : Z = f(X, Y) -

1) 304. (size)
2) blank
3) X1
4) Y1
5) Z
6) Y2
7) Z
8) Y3
9) Z
10) Y4
11) Z
12) X2
13) Y1
14) Z
15) Y2
16) Z
17) Y3
18) Z
19) Y4
20) Z
21) X3
22) Y1
23) Z
24) Y2
25) Z
26) Y3
27) Z
28) Y4
29) Z

- TABLE C : Z = f(Y) -

1) 4. (size)
2) blank
3) blank
4) Y1
5) Z
6) Y2
7) Z
8) Y3
9) Z
10) Y4
11) Z

SUBROUTINE DATARD

Purpose:	Reads user-specified inputs into common block A
Use:	Call DATARD (D, H, N)
Inputs:	N - Unit number of input data file
Outputs:	D - Array into which data is read
	H - Case title, read with 18A4 format
Called by:	AMAIN
Method:	Reads up to 10 values per line in free-field format. See User Instructions for input file format.

SUBROUTINE DBLGIP

PURPOSE: General purpose interpolation program for 2 independent and 1 dependent variables.

USE: CALL DBLGIP (NZ,NPTS,F11,S11,XA,ZA,X,Y,Z,LOG1,LOG2, I3,YA,L)

INPUTS:

NZ	:	Number of Z curves (second independent variable).
NPTS	:	Number of abscissa table values (first indepedent variable).
F11	:	Type of interpolation for first pass (see GIP4 subroutine description for further information).
S11	:	Type of interpolation for second pass (see GIP4 subroutine description for further information).
XA	:	Abscissa array (must contain as many values as specified by NPTS above).
ZA	:	Z array (must contain as many values as specified by NZ above).
X	:	Abscissa value.
Z	:	Z value.
LOG1	:	Logarithm flag for first pass (see GIP4 subroutine description for futher information).

LOG2 : Logarithm flag for second pass (see GIP4 subroutine description for further information).

I3 : Extrapolation flag (see GIP4 subroutine description for further information).

YA : Ordinate array (dependent variable).

L : Integer array contains starting locations of YA for each Z curve. Values must be provided as many as specified by NZ above.

OUTPUTS: Y : Ordinate value.

SUBPROGRAMS USED: GIP4.

COMMON BLOCKS USED: None

CALLED BY: INTRP.

METHOD: Interpolation is made for first independent variable, and then for second independent variable.

RESTRICTIONS:

1) Twenty curves maximum for ordinate array, dependent variable.

2) See GIP4 subroutine description for further restrictions.

SUBROUTINE DELTAD

PURPOSE: Computes pressure balance throughout the engine system.

USE: Call DELTAD (J, K).

INPUT: J - Cycle identifier, first digit of cycle flag (Input Location 7)
K - Schematic identifier, last digit of cycle flag

Component loss coefficients, chamber pressure, fuel turbine pressure ratio, and engine inlet pressure through D array (common block A).

OUTPUTS: Required pump discharge pressures and pressure schedule for a specified engine schematic (via direct update of D array).

SUBPROGRAMS USED: REGEN

COMMON BLOCKS USED: A

CALLED BY: MAIND

METHOD: Calculation for each engine schematic is coded in separate sections of the routine. The input parameters J and K determine which section of the routine is accessed for the given engine schematic.

The engine pressure schedule is calculated starting with known values of chamber pressure, fuel turbine pressure ratio, and valve, injector, and line pressure loss coefficients. Pressures are calculated backwards from the chamber pressure to the pump discharge pressures by adding the pressure drop through each component. Coolant jacket pressure drops are determined by calling REGEN. Where necessary, pressures at a given point are calculated along two branches to determine which governs.

The fuel turbine pressure ratio is set externally by the optimizer and, for parallel turbine configurations, the oxidizer turbine pressure ratio is calculated using known pressures upstream and downstream. For the series turbine configurations, user-defined limits on pressure ratio are also imposed. The gas generator cycle oxidizer turbine pressure ratio is calculated from available pressures and compared with the maximum allowable pressure ratio, input location 89. The lower value is then used.

For the case of an expander cycle with series turbines, the oxidizer turbine pressure ratio is minimized within MAIND thus requiring the particular pressures affected by the oxidizer turbine pressure ratio to be recalculated. This provision is incorporated within DELTAD through entry EXPST. The oxidizer turbine pressure ratio is varied until the oxidizer turbine flowrate matches the fuel turbine flowrate unless it falls below the minimum allowable pressure ratio, input location 82,in which case the minimum value is used and flow is bypassed around the turbine.

RESTRICTIONS: Not applicable.

SUBROUTINE DUMPER

PURPOSE: To perform formatted print of an array to the print file

USE: CALL DUMPER (D,I1,I2,N)

INPUTS:

D	:	Array to be printed.
I1	:	Starting location in array D.
I2	:	End location in array D.
N	:	Logical unit number of print file.

OUTPUTS: None

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: AMAIN

METHOD: An array (or portion of an array) is printed in E-format with 10 values per line.

FUNCTION EFF

PURPOSE: To compute turbine efficiency as a function of velocity ratio and admission for several turbine types.

USE: ARG = EFF (X, Y, K)

INPUTS: X : Admission fraction.

Y : Velocity ratio.

K : Turbine type flag defined as follows.

= 1 : 1-row impulse.
= 2 : 2-row impulse/velocity compounded.
= 3 : 1-stage 50% reaction.
= 4 : 2-stage impulse/pressure compounded.
= 5 : 2-stage reaction.

OUTPUTS: ARG : Turbine efficiency fraction.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: TRBN1D

METHOD:

Efficiency data are incorporated as curve-fits for several turbine types including one-row impulse, two-row impulse, and single-stage 50% reaction turbines. The data cover an admission fraction range of 0.1 to 1.0, and a velocity ratio range of 0.0 to the value at peak efficiency, which is 0.28, 0.48, or 0.70 for two-row impulse, one-row impulse, or single-stage 50% reaction turbines, respectively.

FUNCTION EFFP

PURPOSE: To compute pump efficiency as a function of diameter and specific speed.

USE: ARG = EFFP (DT, XNS)

INPUTS: DT : Pump diameter, inches.

XNS : Pump impeller specific speed, $RPM*GPM^{.5}/FT^{.75}$.

OUTPUTS: ARG : Pump efficiency fraction.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: PUMPD

METHOD: Efficiency data are incorporated as a curve-fit of efficiency as a function of pump diameter and impeller specific speed:

$$ARG = \frac{.84 - .153 \; [\; \ln(XNS) - 7.5 \;]^2 - 12./XNS}{1.538 - .1394 \; MIN(4., DT)}$$

RESTRICTIONS: This routine provides efficiencies for conventional centrifugal pumps with specific speed range from approximately 400 to 2000 . A minimum efficiency of 0.23 is returned to avoid numerical problems for designs outside this range.

SUBROUTINE EHCABC

PURPOSE: To find the equation of a parabola which passes through three points in a plane.

USE: CALL EHCABC (X1, X2, X3, Y1, Y2, Y3, A, B, C)

INPUTS: X1, X2, X3 : X-coordinates of the three defining points

Y1, Y2, Y3 : Y-coordinates of the three defining points

OUTPUTS: A, B, C : Coefficients of the parabola defined as:

$$Y = AX^2 + BX + C$$

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: KINEFF, REGEN.

RESTRICTIONS: None

SUBROUTINE EST

PURPOSE: To cause convergence of the values of two variables by causing a change in the value of the third variable.

USE: CALL EST (L, X, Y, Z, TOL, K, N20)

INPUTS:

L	:	Loop identification number.
X, Y	:	Variables to be compared.
Z	:	Variable to be changed to converge X and Y.
TOL	:	Tolerance limit of comparison.
N20	:	Maximum number of iterations allowed.

OUTPUTS: K : Integer indicator defined as follows.

< 0 : Error such as no. of iterations exceeded.

$= 0$: Converging completed.

> 0 : Back substitution of Z is required, continue iteration.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: IMPULS, MAIND

METHOD:

The Newton-Raphson iteration technique is employed and modified such that the independent variable is not allowed to change value more than 20% per iteration (an empirically derived stability criteria). Consequently, iteration schemes that require Z to start at, or near, or cross zero should be avoided. This is easily accomplished by biasing the value of Z in the call by an appropriate number as follows.

```
CALL EST (22, P1, P2, Z + 100., TOL, K, 20)
```

The subprogram allows calling from the main program 25 nested loops in EST. The subroutine keeps track of loop information. If loop number information is not required to be retained, the same loop number in the call list may be used over and over.

The programmer sets the maximum number of iterations for this subroutine and defines the tolerance of comparison of the dependent variables to be compared, X and Y. The independent variable Z will be changed in the subroutine and could be used to calculate new values of either or both X and Y.

This subroutine may also be used as a means for controlling iteration problems and iteration number in a direct substitution loop by inputting the previous value of the variable as X or Y and the current value as Y or X. Z must then be input as a dummy variable. The current value then must be assigned to the variable being used in the calling routine. The iteration loop will successfully terminate when the absolute value of the difference between the present value and the previous one is less than or equal to the tolerance specified.

RESTRICTIONS:

1) 25 nested loops.

2) Loop ID number L cannot be repeated when using nested loops.

SUBROUTINE EXPL

PURPOSE: To ensure that the selected independent variables lie inside their specified limits.

USE: CALL EXPL (X, N, M, LE, HE, K)

INPUTS:

X	:	Independent variable array dimensioned M by N.
N	:	Number of independent variables.
M	:	Number of complex points plus two (not used in this routine).
LE	:	Array contains lower limit for each independent variable.
HE	:	Array contains upper limit for each independent variable.
K	:	Integer variable which indicates which set of independent variables, ie. X(K,1) thru X(K,N), is being checked.

OUTPUTS: None

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: OPT

METHOD:

The specified set of independent variables are compared to their explicit limits. If exceeded, the independent variable will be moved inside the limits by an amount equal to .000001 of the search field width.

RESTRICTIONS: (See OPT subroutine description).

SUBROUTINE GIP4

PURPOSE: General purpose interpolation program for 1 independent and 1 dependent variables.

USE: CALL GIP4 (X,XA,LX,Y,YA,NPTS,I1,I2,LOGFLG,I3)

INPUTS:

X : Abscissa value, independent variable.

XA : Abscissa array.

LX : Increment added to subscript of XA array to locate successive abscissa values.

YA : Ordinate array.

LY : Increment added to subscript of YA array to locate successive ordinate values.

NPTS : Number of abscissa points.

I1 : Interpolation type flag defined as follows.

- = 0 : Linear.
- = 1 : Power.
- = 2 : Lagrange 3 point (2 before, 1 after).
- = 3 : Lagrange 4 point.
- = 4 : Average Lagrange 3 point.
- = 5 : Power or Lagrange 3 point.
- = 6 : Power or Lagrange 4 point.

I2 : Coefficient flag defined as follows.

- = 1 : New coefficients are computed.

> 1 : Coefficients computed previously are used. This option should only be used if X and XA are exactly the same as in previous calls.

LOGFLG : Logarithm flag defined as follows.

= 0 : Logs not used.

= 1 : Log of Y.

= 2 : Log of X.

= 3 : Log of X and Y.

I3 : Extrapolation flag defined as follows.

= 0 : No extrapolation.

= 1 : Linear extrapolation if necessary.

OUTPUTS: Y : Ordinate value, dependent variable.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: INTRP, DBLGIP.

METHOD:

Several numerical methods are available for interpolation including linear, power, Lagrange, average Lagrange, or combination of power and Lagrange which uses power except where a maximum or minimum occurs. Depending on the interpolation type specified by I1, the dependent variable Y may be computed as a function of independent variable X as follows.

Linear : $Y = aX + b$

Power : $Y = aX^b$

Lagrange 3 point : $Y = aX^2 + bX + c$

Lagrange 4 point : $Y = aX^3 + bX^2 + cX + d$

The current version of the program only uses power and average Lagrange 3 point which is the average of the Lagrange 3 point from left (2 before, 1 after) and right (1 before, 2 after).

RESTRICTIONS:

1) Monotonic curve input format.

2) Power interpolation should not be used where maximum or minimum occurs.

SUBROUTINE IMPL

PURPOSE: To detect implicit constraint violation during optimization.

USE: CALL IMPL (X, N, M, I, J)

INPUTS:

X : Independent variable array dimensioned M by N.

N* : Number of independent variables.

M* : Number of complex points plus two.

I* : Integer variable which indicates the set of independent variables to be checked for implicit constraint violation ($1 \leq I \leq M$).

OUTPUTS:

J : Implicit constraint violation flag defined as follows.

= 0 : no violations.

> 0 : implicit constraint is violated.

SUBPROGRAMS USED: None

COMMON BLOCKS USED: A

* Not used in this routine.

CALLED BY: OPT

METHOD:

This routine compares a calculated parameter against its input lower and/or upper limits. If a violation is found, flag J will be set to a predefined implicit constraint error code. A description of the implicit constraint error codes may be found in the entitled Diagnostic Messages section.

RESTRICTIONS: (See OPT subroutine description).

SUBROUTINE IMPULS

Purpose: To calculate engine performance

Use: Call IMPULS (J, K, JJ)

Inputs:

- J - Cycle identifier, first digit of cycle flag (Input Location 7)
- K - Schematic identifier, last digit of cycle flag
- JJ - Flag, set to zero on first entry and 99 on subsequent entries to avoid recalculating variables that don't change

The following are transmitted via common block A:

Location	Name	Description
1	THRUST	Engine vacuum thrust
2	ENGINE (1)	Nozzle area ratio
4	ENGINE (3)	Engine mixture ratio
106	TURBIN (11)	Turbine inlet temperature
119	PUMPIN (9)	Fuel pump leakage
120	PUMPIN (10)	Oxidizer pump leakage
157	TRBØUT (1)	Fuel turbine exit temperature
158	TRBØUT (2)	Oxidizer turbine exit temperature
168	SPACE (6)	Isentropic exponent, γ
191	PCTLNG	Nozzle percent length
192	ETASEC	Turbine exhaust I_s efficiency
193	DFLG	Dump coolant flowrate
194	ISDUMP	Dump coolant I_s
245	PRES (25)	Chamber pressure
303	DRIVE (1)	GG mixture ratio
320	TRBØX (3)	Oxidizer turbine flowrate
331	TRBFUL (3)	Fuel turbine flowrate

Outputs: All outputs are loaded into common block A:

Location	Name	Description
195	TAU	GG cycle turbine flowrate/thrust chamber flowrate
196	ENGFUL	Engine fuel flowrate
197	ENGØX	Engine oxidizer flowrate
198	PBFFLØ	Preburner or GG fuel flowrate
199	PBØFLØ	Preburner or GG oxidizer flowrate
200	AT	Nozzle throat area
201	CF	Nozzle thrust coefficient
202	FP	Thrust chamber thrust
203	TCMR	Thrust chamber mixture ratio
204	TCIS	Thrust chamber specific impulse
205	ISSEC	GG turbine exhaust specific impulse
249	PRES (29)	Isentropic one-dimensional nozzle exit pressure
250	PRES (30)	Two-dimensional nozzle exit wall pressure
309	DRIVE (7)	Dump coolant flowrate
429	WFUEL	Thrust chamber fuel flowrate
430	WØX	Thrust chamber oxidizer flowrate
455	PERF (1)	Engine delivered vacuum specific impulse
456	PERF (2)	Thrust chamber delivered c-star
457	PERF (3)	Engine delivered sea level specific impulse
458	PERF (4)	Thrust chamber theoretical specific impulse
459	PERF (5)	Thrust chamber theoretical c-star
469	FSL	Engine sea level thrust

SUBPROGRAMS: EST, CSIS, CSTAR1, CSUBF

CALLED BY: MAIND

COMMON BLOCKS: A, IS

METHOD: The method of calculation is outlined in Figure 18. Nozzle exit pressure is first calculated for a one-dimensional isentropic expansion and an empirical correction is applied to estimate the two-dimensional wall pressure. The latter value is used to calculate GG cycle turbine exhaust performance, which is based on an expansion between the turbine exhaust pressure and the nozzle exit wall pressure. This value is also used to predict nozzle flow separation in the atmosphere.

An iteration is required to determine thrust chamber mixture ratio since the engine mixture ratio is fixed at the user-specified input value. The thrust chamber mixture ratio may differ due to turbine flow in the GG cycle and dump coolant and pump leakage flows in all cycles.

Key equations used in engine performance calculations are given below:

$$F_{ENGINE} = F_{THRUST\ CHAMBER} + F_{TURBINE\ EXHAUST} + F_{DUMP}$$

$$F_{THRUST\ CHAMBER} = P_C\ C_F\ A_t$$

$$I_s = \frac{F}{\dot{W}} = \frac{C^* C_F}{g}$$

$$MR = \frac{\dot{W}_{OXIDIZER}}{\dot{W}_{FUEL}}$$

$$\dot{W}_{FUEL} = \frac{\dot{W}_{TOTAL}}{1 + MR} = \frac{\dot{W}_{OXIDIZER}}{MR}$$

$$I_{s_{SL}} = I_{s_{VAC}} - 14.696\ B$$

where $B = \frac{C^*\varepsilon}{P_c g}$.

$$F_{SL} = F_{VAC}\ \frac{I_{s_{SL}}}{I_{s_{VAC}}}$$

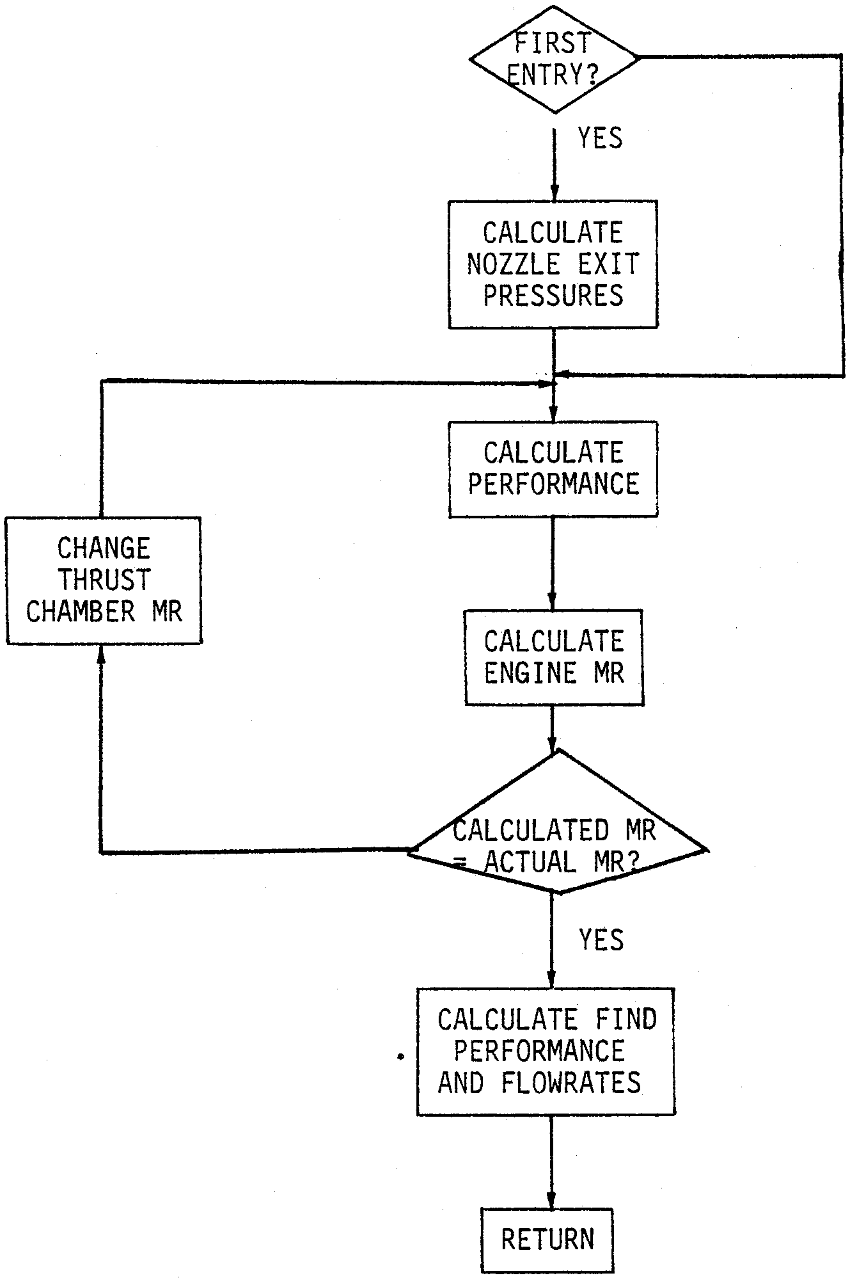

FIGURE 18. ENGINE PERFORMANCE CALCULATION

SUBROUTINE INTRP

PURPOSE: To obtain specific impulse and characteristic velocity theoretical values as a function of chamber pressure , mixture ratio, area ratio and fuel enthalpy.

USE: CALL INTRP (ANSWER,NOPT,HF,XMR,PC,EPS,P)

INPUTS:

NOPT : Option flag defined as follows.
- = 1 : To obtain characteristic velocity.
- = 2 : To obtain specific impulse.

HF : Fuel enthalpy at thrust chamber injector (Kcal/gmole).

XMR : Thrust chamber mixture ratio (oxidizer/fuel).

PC : Chamber pressure (psia).

EPS : Nozzle expansion area ratio.

P : Performance data table.

OUTPUTS: ANSWER
- = Characteristic velocity (ft/sec) if NOPT=1.
- = Specific Impulse (sec) if NOPT=2.

SUBPROGRAMS USED: GIP4, DBLGIP.

COMMON BLOCKS USED: TABSIZ.

CALLED BY: CSIS.

METHOD:

Characteristic velocity is interpolated as a function of PC, XMR and HF. Average Lagrange 3 point method is used in interpolation with XMR and HF. Power method is used in interpolation with PC.

Specific impulse is interpolated as a function of EPS, PC, XMR and HF. Power method is employed in interpolation with EPS, PC and HF. Average Lagrange 3 point is employed in interpolation with XMR.

If any value of the 4 independent variables is outside the range covered by the performance data table provided, linear extrapolation will be performed.

NOTE:

An internal debugging feature may be enabled by modifying the first executable statement within INTRP. If this statement is altered to read:

```
IDEBUG = 1
```

A detailed summary of INTRP's function will be printed. This feature provides a helpful way to insure the performance data are in the proper format. However, a very large amount of printed output will be generated if a full optimization is run with this debugging feature enabled.

SUBROUTINE KINEFF

PURPOSE: To obtain thrust chamber kinetic efficiency as a function of chamber pressure, mixture ratio, nozzle expansion area ratio and throat radius.

USE: CALL KINEFF (PC,MR,EPS,RT,EFFK)

INPUTS:

PC	:	Chamber pressure, psia.
MR	:	Chamber mixture ratio (oxidizer/fuel).
EPS	:	Nozzle expansion area ratio.
RT	:	Throat radius, in.

OUTPUTS:

EFFK	:	Kinetic efficiency.

SUBPROGRAMS USED: CURVES, EHCABC.

COMMON BLOCKS USED: EFFK.

CALLED BY: CSIS.

METHOD:

Kinetic efficiencies are interpolated within the input data tables with respect to PC, MR and EPS at throat radii of 0.1, 1.0, and 10.0 inches (2 decades). A parabola is then fitted through these 3 points, and used in computing the actual efficiency at the given throat radius.

SUBROUTINE MAIND

PURPOSE: Controls Engine Balance and Optimization Calculations

USE : CALL MAIND (JCYCLE, KCYCLE)

INPUTS : All Inputs are Transmitted via Common Block A

Location	Name	Description
3	ENGINE (2)	Chamber pressure (initial guess if location 11 = -2)
4	ENGINE (3)	Engine mixture ratio
5	ENGINE (4)	Fuel bypass fraction
6	ENGINE (5)	Propellant combination flag
7	ENGINE (6)	Engine cycle flag
11	ENGINE (10)	Optimizer objective flag
14	ENGINE (13)	Minimum chamber pressure (if location 11 = -2)
15	ENGINE (14)	Maximum chamber pressure (if location 11 = -2)
16	ENGINE (15)	Coolant bypass fraction
23	XIMPL (7)	Fuel pump maximum diameter ratio
24	XIMPL (8)	Oxidizer pump maximum diameter ratio
77-82	XEXPLL(1)-(6)	Optimizer variable lower limits
84-89	XEXPLU(1)-(6)	Optimizer variable upper limits
94	ALPHA	Optimizer reflection factor
95	TOL	Optimizer termination tolerance
96	TURBIN(1)	Turbine size flag
97	TURBIN(2)	Maximum turbine tip speed

98	TURBIN(3)	Minimum turbine blade height
99	TURBIN(4)	Maximum turbine AN^2
100	TURBIN(5)	Fuel turbine type flag
101	TURBIN(6)	Oxidizer turbine type flag
102	TURBIN(7)	Minimum turbine pitch diameter
103	TURBIN(8)	Maximum turbine hub/tip ratio
104	TURBIN(9)	Fuel turbine shaft sizing flag
105	TURBIN(10)	Oxidizer turbine shaft sizing flag
106	TURBIN(11)	Fuel turbine inlet temperature
107	TURBIN(12)	Oxidizer turbine inlet temperature
113	PUMPIN(3)	Fuel engine inlet NPSP
114	PUMPIN(4)	Oxidizer engine inlet NPSP
115	PUMPIN(5)	Fuel kick pump flag
116	PUMPIN(6)	Oxidizer kick pump flag
117	PUMPIN(7)	Number of fuel pump stages
118	PUMPIN(8)	Number of oxidizer pump stages
119	PUMPIN(9)	Fuel pump leakage
121	PUMPIN(11)	Fuel pump inducer flow coefficient
122	PUMPIN(12)	Oxidizer pump inducer flow coefficient
151-156	GUESS(1)-(6)	Optimizer variable initial guesses

OUTPUTS: JCYCLE - Cycle identifier, first digit of cycle flag (Input Location 7)

KCYCLE - Schematic identifier, last digit of cycle flag

The following outputs are loaded into common block A:

Location	Name	Description
43-76	XIMPL(27)-(60)	Implicit constraint flags
141	DELTAP(11)	Combustor coolant flowrate
142	DELTAP(12)	Nozzle coolant flowrate
157	TRBOUT(1)	Fuel turbine exit temperature

158	TRBOUT(2)	Oxidizer turbine exit temperature
198	PBFFLO	Preburner or GG fuel flowrate
199	PBOFLO	Preburner or GG oxidizer flowrate
222	PRES(2)	Engine inlet oxidizer NPSH
229	PRES(9)	Engine inlet fuel NPSH
230	PRES(10)	Fuel turbine pressure ratio
245	PRES(25)	Chamber pressure
307	DRIVE(5)	Oxidizer kick pump flowrate
308	DRIVE(6)	Fuel kick pump flowrate
340	TURPMP(1)	Oxidizer boost pump minimum delta-P
341	TURPMP(2)	Fuel boost pump minimum delta-P
344	TURPMP(5)	Oxidizer turbine hub/tip ratio
345	TURPMP(6)	Fuel turbine hub/tip ratio
431	WAVAIL	Available turbine flowrate
432	WREQD	Required turbine flowrate
439	OBJECT	Optimizer object function
468	MRPBO	Overall preburner or GG mixture ratio

SUBPROGRAMS: PRPRP, PRØCES, IMPULS, DELTAD, TEMP, ZERØ, PUMPD, PMPCNV, TRBN1D, EST, EXPST (entry in DELTAD), ØPT

CALLED BY: AMAIN

INTERNAL ARRAYS:

A(9) - Used for PUMPD inputs

B(14) - Used for PUMPD outputs

C(17) - Used for TRBN1D inputs

D(16) - Used for TRBN1D outputs

ENGIN(600) - A single array corresponding to common block A through an EQUIVALENCE statement

X(17,7) - Optimizer complex array

XL(7) - Optimizer variable lower limits

XU(7) - Optimizer variable upper limits

Method: The overall logic of MAIND is shown in Figure 19. A complete balance is first performed with the input initial guesses on the optimizer variables. The implicit constraints are checked on the first OPT call and if none are violated, a new set of optimizer variables are selected by OPT. The complex is first filled by selecting values above and below the initial guess on each variable and new points are then projected to improve the object function.

During the optimization process the implicit constraints are checked for each point in subroutine IMPL, called by OPT. The implicit constraint array, XIMPL, in common block A, contains two types of variables. Locations 1-26 are input locations for various limits which are compared with the calculated values in IMPL. Locations 27-60 are flags set by MAIND to indicate a constraint violation. These flags are checked in IMPL and, if 0.0, no violation occurred; if 1.0, a constraint was violated.

MAIND is primarily devoted to controlling the balance and optimization logic and setting up inputs for the more specialized subroutines. There are no complex calculations in the routine but it is suggested that the logic be well understood before modifications are made.

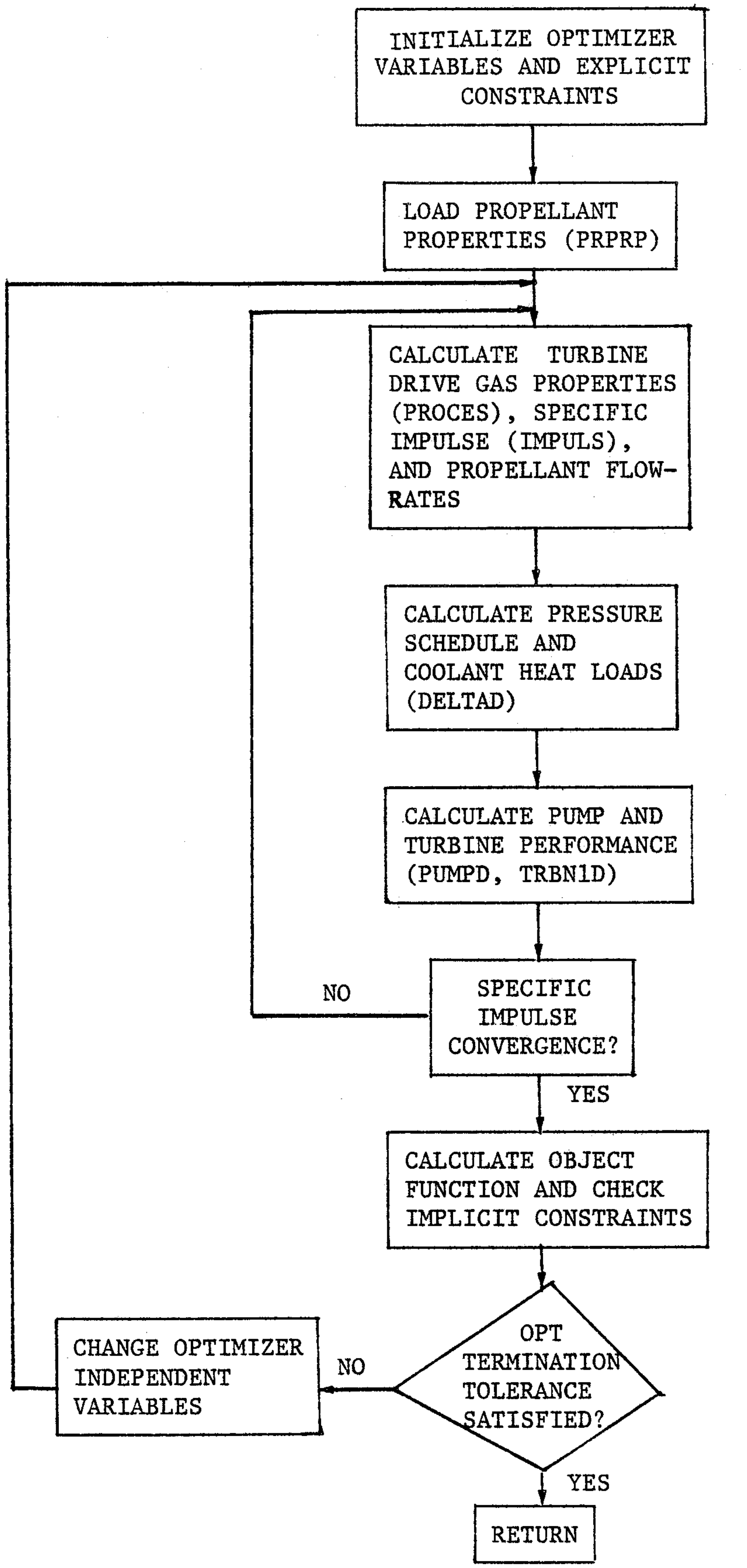

FIGURE 19. SUBROUTINE MAIND FLOW CHART

SUBROUTINE OPT

PURPOSE: To determine the set of independent variables which yield the optimum of a constrained equation or system of equations.

USE: CALL OPT (X, N, M, V, LE, HE, TOL, KK)

INPUTS:

X : Independent variable array which has a dimension of M by N. The locations from (1,1) to (1,N) of this array initially contain the first guess of independent variables. In addition, the initial value of location (2,1) of this array must be set to the reflection factor (ALPHA) which must be greater than 1.0 (default = 1.3).

N : Number of independent variables.

M : Number of points in the complex plane plus 2. (suggest 2N+3)

V : Value of function to be minimized.

LE : Array contains the lower limit for each independent variable.

HE : Array contains the upper limit for each independent variable.

TOL : Optimization tolerance. (suggest .00001 < TOL < .001)

OUTPUTS: KK : An integer flag used as both input and output. KK must be set initially to -1 signaling the start of a new optimization, and KK must not be altered by the calling program thereafter. Upon return to the calling program, the value of KK is defined as follows.

- < 0 : error occurs where KK is an implicit constraint error code. If KK=-99, an internal search failure has resulted due to unusual circumstances created by the constraints.
- = 0 : optimum solution found and the locations from (1,1) to (1,N) of X array contain the optimum set of independent variables.
- > 0 : Back substitution of X(KK,1) thru X(KK,N) to the calling program is required (KK may be from 1 to M).

SUBPROGRAMS USED: EXPL, IMPL

COMMON BLOCKS USED: None

CALLED BY: MAIND

METHOD:

The Box complex method of optimization is used (Box, M. J., Computer Journal 8, No. 1, pg. 42, 1965). This method is an extension of the so-called "simplex method" for unconstrained minimization. The complex method (so called because it involves a "complex" of points) is capable of finding the minimum of a function, which may not be expressible conveniently in closed form, subject to constraints. Maximization can also be achieved by minimizing the negative of the desired object function.

The optimization is constrained implicitly and explicitly by input limits. Explicit constraints are minimum and maximum limits on the independent variables. Implicit constraints are design limits which reflect technology, life, and other requirements on the final design.

Figure __ illustrates schematically the constrained optimization process. This process consists of initially selecting a complex of points where a "point" consists of a system balance with a particular set of independent variables. The initial complex can be chosen at random as long as no constraints are violated. The object function (for example -Pc) is calculated at each point in the complex, and the vertex of the worst point (i.e., lowest Pc) is found. This worst point is then replaced by a point which is determined by projecting a vector from the worst point in the direction of the centroid (arithmetic average) of the complex for a distance equal to the reflection factor times the distance from the worst point to the centroid. The iteration process is continued until the convergence criterion is satisfied as below:

$$\left[\frac{\sum_{i=1}^{M-2} (V_i - V_c)^2}{(M - 2) V_c^2} \right]^{1/2} \leq \text{TOL}$$

where V is the value of the object function, and the subscripts c and i denote the centroid and the ith complex point, respectively.

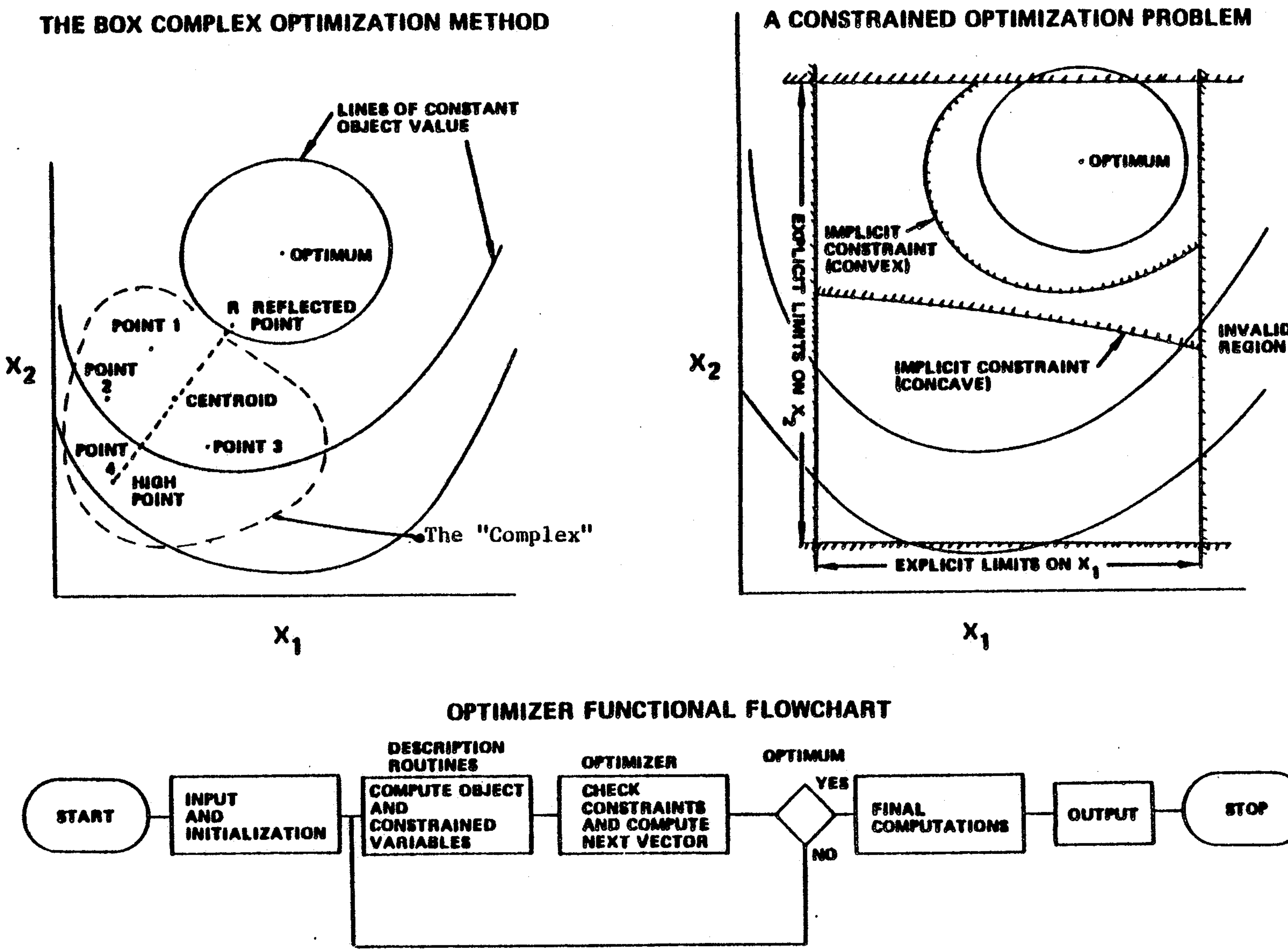

Figure 20. System Optimization Process

RESTRICTIONS:

(1) A maximum value of M is presently 17, but this can be increased or decreased by modifying the DIMENSION statement.

(2) A maximum value of N is presently 7, but this can be increased or decreased by modifying the DIMENSION statement.

(3) A subroutine named IMPL must be provided in order to check for any violations on implicit constraints (see IMPL subroutine description for more details).

(4) The values of the independent variables should not be altered by the calling programs during an optimization.

(5) A unique (global, rather than local) optimum must exist.

(6) Constraints must be concave; convex constraints can cause multiple solutions which depend on the starting point.

Subroutine PMPCNV

Purpose: This routine places pump routine outputs in the proper common block locations, and calculates several inducer parameters.

Use: Call PMPCNV (A, B, W, X1, X2, K)

Inputs:

A - Array containing PUMPD inputs

B - Array containing PUMPD outputs

X1 - Inducer inlet hub/tip ratio

X2 - Inducer $\frac{NPSH}{C_m^2/2g}$

K - 0 for main pump, -11 for kick pump

Outputs: W - Corresponds to common block A array PMPFUL, FULKCK, PMPØX, or PMPKCK, depending upon which pump the call is associated with

Called by: MAIND

Method: The following elements of the W-array are calculated within the routine:

W(5) - Inducer diameter, D_i = impeller diameter x diameter ratio

W(6) - Inducer inlet flow area, $A_i = .7854 \times D_i^2 \times (1-X1^2)$

W(1) - Inducer inlet flow velocity, $C_m = \dfrac{144 \times \dot{W}}{\rho \times A_i}$

where $\dot{W}$ = flowrate, lb/sec

ρ = density, lb/ft^3

W(11)- Inducer required NPSH = $\dfrac{X2 \times C_m^2}{2g}$

W(2) - Inducer tip speed = impeller tip speed x diameter ratio

SUBROUTINE PRINT

Purpose:	To provide a printed output of the final engine balance
Use:	CALL PRINT (D, H, JCYCLE, KCYCLE)
Inputs:	D - Array corresponding to common block A
	H - Case title in 18A4 format
	JCYCLE - Cycle identifier, first digit of engine cycle flag (input location 7)
	KCYCLE - Schematic identifier, third digit of engine cycle flag
Outputs:	None, other than printed output
Called by:	AMAIN
Method:	Output is written to file 6

SUBROUTINE PROCES

PURPOSE: Computes turbine drive gas process properties.

USE: Call PROCES (D, J, K, JPROP)

INPUT: JPROP - Propellant combination flag

J - Cycle identifier, first digit of cycle flag (Input Location 7)

K - Schematic identifier, last digit of cycle flag

Drive gas temperature and heat of formation (taken from D array)

OUTPUTS: Drive gas mixture ratio, molecular weight, process gamma, and specific heat are output in D (303)-D(306), D(310)-D(311), and D(315)-D(316).

SUBPROGRAMS USED: CURVES

COMMON BLOCKS USED: GGDATA

CALLED BY. MAIND

METHOD: Process gas properties are either calculated directly from functions representing curve-fit data (provided within this routine) or interpolated from tabularized data (initialized with subroutine BDATA) by subroutine CURVES. The input parameters JPROP, J and K determine which data are employed for the specific engine configuration and propellant combination. Inline statement functions containing curve-fits provide the properties listed below:

FLUID	FUNCTION	PROPERTY
Fuel-rich	TR1(T,H)	Mixture ratio
O_2/H_2	TR2(R)	Molecular weight
Fuel-rich	TR3(T,H)	Mixture ratio
O_2/CH_4	TR6(R,H)	Molecular weight
Oxid-rich	TR4(T)	Mixture ratio
O_2/CH_4	TR7(R)	Molecular weight
	TR8(R)	Gamma
	TR9(R)	Specific heat
Fuel-rich	TR10(T,P)	Mixture ratio
O_2/RP-1	TR13(T)	Specific heat
	TR14(T)	Gamma
	TR15(T)	Molecular weight
Oxid-rich	TR11(T,H)	Mixture ratio
O_2/RP-1	TR12(R)	Molecular weight
Oxid-rich	TR16(T)	Mixture ratio
O_2/C_3H_8	TR17(R)	Mixture ratio
	TR18(R)	Gamma
	TR19(R)	Specific heat

RESTRICTIONS: Applicable range of the data tables (ref: subroutine BDATA description) should not be exceeded.

SUBROUTINE PRPRP

Purpose:	To select propellant properties for the specified propellants
Use:	CALL PRPRP (D)
Inputs:	Inputs and outputs are passed through array D, which corresponds to common block A D(6) - Propellant combination flag

Outputs:	D (206)	Fuel density, lb/ft^3
	D (207)	Oxidizer density, lb/ft^3
	D (208)	Fuel molecular weight, lb/lb-mole
	D (209)	Oxidizer molecular weight, lb/lb-mole
	D (210)	Fuel engine inlet heat of formation K cal/gm-mole
	D (211)	Oxidizer engine inlet heat of formation, Kcal/gm-mole
	D (212)	Fuel $\frac{NPSH}{C_m^2/2g}$, the empirical ratio of the required inducer NPSH to the inlet velocity head (C_m = inducer inlet velocity)
	D (213)	Oxidizer $\frac{NPSH}{C_m^2/2g}$
	D (214)	Fuel engine inlet enthalpy, btu/lb

Called by:	MAIND
Method:	Propellant properties are stored in a data statement and loaded into common based on the propellant combination flag

SUBROUTINE PUMPD

PURPOSE: To calculate centrifugal pump performance and geometry

USE: Call PUMPD (A, W)

INPUTS:

A (1) - Pump pressure rise, ΔP, psi

A (2) - Pump flowrate, $\dot{W}$, lb/sec

A (3) - Propellant density, ρ, lb/ft^3

A (4) - Inducer flow coefficient, ϕ

A (5) - Number of stages, n

A (6) - Maximum diameter ratio (inlet/outlet)

A (7) - Maximum bearing DN, mm-RPM

A (8) - Flag: 0 - shaft size based on critical speed
>0 - shaft size based on shear stress

A (9) - Rotational speed, N, RPM

OUTPUTS:

W (1) - Required horsepower, HP

W (2) - Pump overall efficiency, η

W (3) - Rotational speed, N, RPM (the speed may be lowered from the input speed; if so, an implicit constraint will be violated.)

W (4) - Impeller head coefficient, Ψ

W (5) - Number of iterations to converge

W (6) - Diameter ratio (inlet/outlet)

W (7) - Bearing DN based on critical speed, mm-RPM

W (8) - Impeller tip diameter, D_t, in.

W (9) - Impeller tip width, h_b, in.

W (10) - Specific speed per stage, Ns $\frac{RPM(GPM)^{1/2}}{ft^{3/4}}$

W (11) - Bearing DN based on shear stress, mm-RPM

W (12) - Impeller tip speed, U_t, ft/sec

W (13) - Effective density, ρ, lb/ft^3

W (14) - Head rise, ΔH, ft

SUBPROGRAMS: EFFP

METHOD: Pump analysis is based on geometric, physical, and empirical relationships. The solution is iterative and an efficiency must be assumed to calculate the parameters required to determine the actual efficiency. Key equations are outlined below:

Head and flow are first calculated,

$$\Delta H = 144 \Delta P/\rho$$
$$Q = 448.9\ \dot{W}/\rho$$

With an assumed efficiency, the required horsepower is:

$$HP = \frac{.2618\ \dot{W}\ \Delta P}{\eta\rho}$$

The maximum RPM based on the DN limit is next calculated, and if lower than the input RPM, an implicit constraint violation will occur. The actual DN limit, however, is based on the turbine, rather than pump, horsepower, since a kick pump may be employed.

The specific speed is:

$$N_s = \frac{N\sqrt{Q}}{H^{3/4}n} \quad \text{(per stage)}$$

and the head coefficient and flow coefficient are:

$$\Psi = .685 - .157 \left(\frac{N_s}{1000}\right)^{2/3}$$

$$\emptyset = .00364 \sqrt{N_s}$$

The tip diameter is:

$$D_t = \frac{229}{N} \sqrt{\frac{g\ \Delta H}{n\Psi}}$$

If the tip diameter is less than 4 inches a correction is applied to correct for reduced efficiency:

$$D_t = -X2 + \sqrt{X2^2 + 1.538X1}$$

where

$$X1 = \frac{1.02g\,\Delta H}{n\Psi\,(N/229)^2}$$

The tip speed is:

$$U_t = D_t\ N/229$$

and the head coefficient is recalculated:

$$\Psi = \frac{g\ \Delta H}{n\ U_t 2}$$

The actual efficiency is next calculated as a function of diameter and specific speed by function EFFP and the calculations are repeated until the efficiency converges. Additional parameters are then calculated:

$$\text{Diameter ratio} = \frac{.003607\sqrt{\Psi}\ N_s{}^{3/4}}{\phi^{1/3}}$$

$$DN = 63.81\ HP^{1/4}\ N^{3/4} \quad \text{(based on critical speed)}$$

$$DN = 50.88\ HP^{1/3}\ N^{2/3} \quad \text{(based on shear stress)}$$

$$h_b = \frac{.146\ Q}{D_t\ \phi\ U_t}$$

If the propellant is hydrogen, compressibility effects must be considered. This is done by calculating the ratio of the isentropic efficiency to the incompressible efficiency:

$$\frac{\eta_s}{\eta_i} = 1 - .008 \left(\frac{\Delta P}{100}\right)^m$$

where,

$$m = 1.3894515 - .38373341\,\eta_i - 3.5234337\,\eta_i^2 + 6.2111123\,\eta_i^3 - 3.5877925\,\eta_i^4$$

and,

$$\eta_i = \eta \text{ from EFFP}$$

The isentropic head rise is also calculated:

$$\Delta H_i = 361.88148 + 31525.714 \left(\frac{\Delta P}{1000}\right) - 596.95279 \left(\frac{\Delta P}{1000}\right)^2 + 16.12084 \left(\frac{\Delta P}{1000}\right)^3$$

The actual head rise is then:

$$H = \frac{\Delta Hi}{\eta_s/\eta_i}$$

and the effective density is the value which relates ΔH and ΔP.

$$\rho = 144\ \Delta P/\Delta H$$

SUBROUTINE REGEN

PURPOSE: Calculates cooling jacket heat loads and pressure drops.

USE: Call REGEN (D).

INPUT: D array for propellant combination flag, chamber pressure, thrust, and thrust chamber design cycle life.

OUTPUTS: Thrust chamber cooling jacket heat load and pressure drop.

SUBPROGRAMS USED: EHCABC

COMMON BLOCKS USED: None

CALLED BY. DELTAD

METHOD: Cooling jacket heat load and pressure drop are calculated from empirical relations provided within this routine as polynominal functions of thrust, chamber pressure, and thrust chamber cycle life for each propellant combination. Propellant enthalpies entering the combustor and preburner or GG are also calculated. Linear or quadratic interpolation is used between points, depending on whether two or three points are available.

RESTRICTIONS: Limited to range of built-in data. Current data are summarized below:

PROPELLANT	DATA
O_2/CH_4	Combustor delta-P (life=100, F=200 K)
	Combustor delta-P (life=100, F=500 K)
	Combustor heat load (F_{s1}=600 K)
	Nozzle heat load (F_{s1}=600 K)
O_2/H_2	Combustor delta-P (life=100, F=200 K)
	Combustor delta-P (life=100, F=500 K)
O_2/C_3H_8	Combustor delta-P (life=100)
	Combustor delta-P (life=150)
	Combustor delta-P (life=250)
	Combustor heat load (F_{s1}=600 K)
	Nozzle heat load (F_{s1}=600 K)

SUBROUTINE TEMP

Purpose:	Provides fuel temperature as a function of pressure and enthalpy		
Use:	CALL TEMP (J, P, H, T)		
Inputs:	J - Fuel flag,	1	H_2
		2	CH_4
		3	RP-1
		4, 5	C_3H_8
		6	MMH
	P - Pressure, psia		
	H - Enthalpy, BTU/lb		
Outputs:	T - temperature, °R		
Called by:	MAIND		
Method:	Curve-fits of fuel property data are incorporated as statement functions.		
Restrictions:	Data are currently in the program for only two fuels, H_2 and CH_4. Fuel temperatures are printed by the program but are not actually used for program calculations unless an expander cycle is specified, in which case an accurate turbine inlet temperature is needed.		

SUBROUTINE TRBN1D

PURPOSE: To calculate gas turbine performance and geometry

USE: CALL TRBN1D (A, R, W)

INPUTS:

A (1)	Inlet temperature, T_i, R
A (2)	Blockage fraction (1-admission), b
A (3)	Turbine size flag: 1 -- large (>3-inch diameter) 0 -- small (~2-inch diameter)
A (4)	Minimum blade height, inch
A (5)	Maximum tip speed, ft/sec
A (6)	Turbine gas molecular weight, MW, lb/lb-mole
A (7)	Maximum centrifugal stress, AN^2, $(\text{in-rpm})^2$
A (8)	Turbine gas isentropic exponent, γ
A (9)	Turbine gas specific heat, C_p, Btu/lbm-R
A (10)	Turbine exit pressure, P_e, psia
A (11)	Turbine type flag: 1 = 1 row impulse 2 = 2 row impulse/velocity compounded 3 = 1 stage 50% reaction 4 = 2 stage impulse/pressure compounded 5 = 2 stage reaction
A (12)	Not used
A (13)	Required horsepower, HP
A (14)	Shaft speed, N, rpm
A (15)	Minimum pitch diameter, inch
A (16)	Maximum hub-to-tip ratio
A (17)	Diameter of driven pump, inch
R	Pressure ratio, PR

OUTPUTS:	W (1)	Turbine efficiency, η
	W (2)	Pitch diameter, Dm, inch
	W (3)	Flowrate, $\dot{W}$, lbm/sec
	W (4)	Horsepower, HP
	W (5)	First row or stage blade height, h_b, inch
	W (6)	Second row or stage blade height, inch
	W (7)	Shaft speed, N, rpm
	W (8)	Velocity ratio, u/Co
	W (9)	Tip speed, U_t, ft/sec
	W (10)	Turbine annulus area x speed squared, AN^2, $(\text{in-rpm})^2$
	W (11)	Number of iterations for turbine design convergence
	W (12)	Bearing DN, mm x rpm (based on critical speed)
	W (13)	Blockage (1 - admission), b
	W (14)	Exit temperature, T_e, R
	W (15)	Obsolete
	W (16)	Obsolete

SUBPROGRAMS: EFF

CALLED BY: MAIND

METHOD: The turbine analysis is designed to maximize efficiency within stress and geometric constraints. An iterative solution is required since an efficiency must be assumed to calculate the parameters needed to calculate the actual efficiency.

The efficiency is a function of admission and U/C_o, where U is the pitchline velocity and C_o is the nozzle spouting velocity. The admission, rotating speed, and pressure ratio are varied externally by the optimizer so, within the routine, efficiency is maximized by selecting the highest pitch diameter which violates no constraints, thus maximizing the pitchline velocity.

METHOD: (cont.)

The pitch diameter is calculated according to five criteria and the smallest value is used:

(1) Maximum tip speed
(2) Minimum blade height
(3) (U/C_o) max (U/C_o is not allowed to exceed the value at which peak efficiency occurs.)
(4) Maximum hub/tip ratio
(5) Three times the pump impeller diameter

The routine will generally return a design which meets the input constraints and may change the input values of admission and rpm. If the minimum pitch diameter and minimum blade height result in too much flow area the percent admission will be reduced. The rpm will be reduced if the following occur:

(1) The maximum value of AN^2 is exceeded
(2) The input values of rpm, minimum pitch diameter, and minimum blade height result in a tip speed higher than the input limit.
(3) The input values of rpm and minimum pitch diameter result in a value of U/C greater than the value at which peak efficiency occurs.

A change in admission or rpm will result in an implicit constraint flag being raised in subroutine MAIND.

Key equations are outlined below:

$$C_o = 315\sqrt{\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{T_i}{MW}\right)\left[1-\left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Where C_o is the nozzle spouting velocity, ft/sec

$$\dot{W} = \frac{HP}{1.415\ \eta\, C_p\ T_i\left[1-\left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$Ae = \frac{1545 \dot{W} T_i}{MW\ P_e\ C_o\ PR^{\frac{\gamma-1}{\gamma}}}$$

where Ae is the nozzle exit area, in^2

$$\ell = \frac{Ae}{\pi\ D_m\ \sin 17\ (1-b)}$$

where ℓ is the nozzle discharge height, in., and 17° is the nozzle angle

$$h_b = \ell/.8264 = \frac{1.0886\ Ae}{.8264\ D_m\ (1-b)}$$

the constant .8264 accounts for friction, discharge coefficient, etc.

$$U = \frac{D_m N}{229}$$

$\eta = f\ (U/C_o,\ 1\text{-}b)$ from function EFF

$$U_t = \frac{\left(D_m + h_b\right)N}{229}$$

$$AN^2 = \pi\ D_m h_b N^2$$

$$Te = T_i \left[1 - \eta + \eta \left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

The above equations are for an impulse turbine, where the entire expansion occurs in the nozzles. In a reaction turbine, part of the expansion occurs in the nozzles and the rest in the rotor blades. This affects the nozzle design so the following adjustments are made to C_o, PR, and P_e for use in the nozzle exit area calculation:

$$C_{o,R} = C_o / \sqrt{2}$$

$$PR,_R = \left\{ .5 \left[1 + \left(\frac{1}{PR} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{\gamma}{1-\gamma}}$$

$$P_{e,R} = \frac{P_e \, PR}{PR,_R}$$

Two-stage designs are analyzed by calculating geometry for the first stage only. The first stage is designed based on providing half the required horsepower with a pressure ratio equal to the square root of the overall pressure ratio. The resulting flowrate is then adjusted to account for the reduced gas temperature entering the second stage.

Turbine type selection is based on achieving the highest efficiency for a given application. Figure 21 shows efficiency characteristics of the turbine types included in the routine. The efficiency shown includes only the exit velocity and blade losses and will be higher than values provided by function EFF. The U/C_o for the two-stage (not including two-row) designs is for both stages. The value per stage, which is printed by the program, is equal to approx. $\sqrt{2}$ times the value shown. The higher values of U/C_o are associated with lower pressure ratios, although other factors also have some effect.

The two-row velocity-compounded turbine is generally the first choice for gas generator cycles, due to the high pressure ratios. Either impulse or reaction, one- or two-stage designs may be preferred for expander or staged combustion cycles, depending on pressure ratio, gas properties, and operating limits. Once a balance has been achieved, the resulting efficiency and U/C_o can be used with Figure 21 to indicate if another turbine type might improve performance.

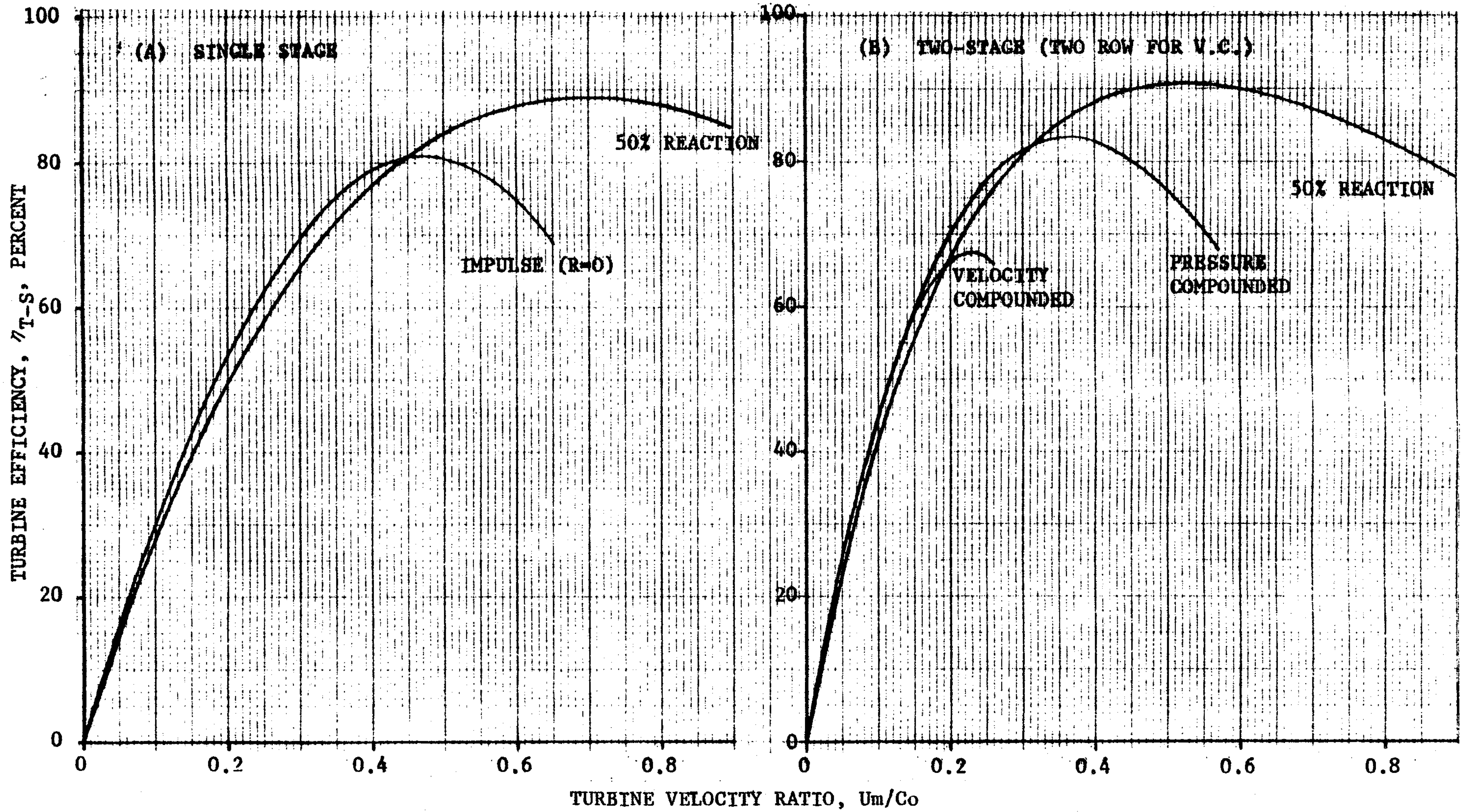

Figure 21. Turbine Efficiency Characteristics

SUBROUTINE ZERO

PURPOSE: To set the specified locations of an array equal to zero.

USE: CALL ZERO (D, J, K)

INPUTS:

- D : Array to be cleared.
- J : First location of array D to be cleared.
- K : Last location of array D to be cleared.

OUTPUTS: None

SUBPROGRAMS USED: None

COMMON BLOCKS USED: None

CALLED BY: AMAIN, MAIND, PRINT.

COMMON BLOCK DESCRIPTION

Program input and ouput variables are contained in labeled common block /A/. These variables are listed by name and number in Table 7, along with default values for the inputs and the routines which calculate or use each variable. Explanatory notes, where required, are given at the end of the table. User input instructions and descriptions of other common blocks are included in the User Instructions and Code Structure sections. Input values most likely to be changed from case to case are emphasized in Table 7 by a box around the location number. Defaults are either arbitrary or based on state-of-the-art or good design practice; where appropriate, these values are discussed in the notes at the end of the table.

TABLE 3

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
$\boxed{1}$	THRUST	Engine vacuum thrust	Lbf	500,000		IMPULS	Input
$\boxed{2}$	ENGINE (1)	Nozzle expansion area ratio	None	35		MAIND	Input
$\boxed{3}$	ENGINE (2)	Chamber pressure (initial guess if ENGINE (10) = -2)	psia	1500		MAIND	Input
$\boxed{4}$	ENGINE (3)	Engine mixture ratio, oxidizer/fuel (by weight)	None	3.5		IMPULS	Input
$\boxed{5}$	ENGINE (4)	Fuel bypass fraction (of total fuel that is not used for preburner)	None	0.1	1	MAIND	Input
$\boxed{6}$	ENGINE (5)	Propellant combination (See Page 30)	None	2		PROCES	Input
$\boxed{7}$	ENGINE (6)	Engine cycle (See Page 31)	None	101		MAIND	Input
8	ENGINE (7)	NCU*					
9	ENGINE (8)	>0 Eliminate initial printout	Flag	0	2	AMAIN	Input
10	ENGINE (9)	Coolant circuit option: = 0 parallel cooling circuit = 1 series cooling circuit	Flag	0	3	MAIND	Input
$\boxed{11}$	ENGINE (10)	Minimization objective: = 0 coolant pump discharge pressure = 1 secondary (turbine exhaust) flow = -2 maximize Pc	Flag	-2	4	MAIND	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
12	ENGINE (11)	Flag: check initial guess only = 0 No = 1 Yes = 2 Yes, no printout	Flag	0	5	MAIND	Input
13	ENGINE (12)	Max. number of optimizer iterations	None	2000	6	MAIND	Input
14	ENGINE (13)	Min. P_c limit (if ENGINE (10) = -2)	psia	1400		EXPL	Input
15	ENGINE (14)	Max. P_c limit(if ENGINE (10) = -2)	psia	6000		EXPL	Input
16	ENGINE (15)	Cooling jacket bypass fraction	None	0	7	MAIND	Input
17	XIMPL (1)	Main Fuel pump min. impeller tip width	Inches	0.03		MAIND	Input
18	XIMPL (2)	Main oxidizer pump min. impeller tip width	Inches	0.03		MAIND	Input
19	XIMPL (3)	Main fuel pump min. inducer diameter	Inches	1.0		IMPL	Input
20	XIMPL (4)	Main oxidizer pump min. inducer diameter	Inches	1.0		IMPL	Input
21	XIMPL (5)	Main fuel pump max. DN	mm-rpm	1.8 E6	8	MAIND	Input
22	XIMPL (6)	Main oxidizer pump max. DN	mm-rpm	1 E6	8	IMPL	Input
23	XIMPL (7)	Main fuel pump inlet/outlet max. diameter ratio	None	.8	9	MAIND	Input
24	XIMPL (8)	Main oxidizer pump inlet/outlet max. diameter ratio	None	.8	9	MAIND	Input
25	XIMPL (9)	Main fuel pump max. impeller tip speed	ft/sec	2000	8	IMPL	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
26	XIMPL (10)	Main oxidizer pump max. impeller tip speed	ft/sec	2000	8	IMPL	Input
27	XIMPL (11)	Main fuel pump max. inducer tip speed	ft/sec	1600	8	IMPL	Input
28	XIMPL (12)	Main oxidizer pump max. inducer tip speed	ft/sec	1600	8	IMPL	Input
29	XIMPL (13)	Main fuel pump max. discharge pressure	psia	1 E6		IMPL	Input
30	XIMPL (14)	NCU					
31	XIMPL (15)	Main fuel pump min. impeller stage specific speed	rpm-gpm ft 3/4	400		IMPL	Input
32	XIMPL (16)	Main oxidizer pump min. impeller stage specific speed	rpm-gpm ft 3/4	400		IMPL	Input
33	XIMPL (17)	Main fuel pump max. impeller stage specific speed	rpm-gpm ft 3/4	2200		IMPL	Input
34	XIMPL (18)	Main oxidizer pump max. impeller stage specific speed	rpm-gpm ft 3/4	2200		IMPL	Input
35	XIMPL (19)	Main fuel pump min. impeller tip diameter	Inches	2		MAIND	Input
36	XIMPL (20)	Main oxidizer pump min. impeller tip diameter	Inches	2		MAIND	Input
37	XIMPL (21)	Main fuel pump max. impeller tip diameter	Inches	100		IMPL	Input
38	XIMPL (22)	Main oxidizer pump max. impeller tip diameter	Inches	100		IMPL	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
39	XIMPL (23)	NCU					
40	XIMPL (24)	NCU					
41	XIMPL (25)	NCU					
42	XIMPL (26)	NCU					
43	XIMPL (27)	Oxidizer pump NPSH too high	Flag			IMPL	Output
44	XIMPL (28)	Fuel pump NPSH too high	Flag			IMPL	Output
45	XIMPL (29)	NCU					
46	XIMPL (30)	NCU					
47	XIMPL (31)	Main fuel pump speed reduced by turbine routine	Flag			MAIND	Output
48	XIMPL (32)	Main oxidizer pump speed reduced by turbine routine	Flag			MAIND	Output
49	XIMPL (33)	Main fuel turbine admission reduced	Flag			MAIND	Output
50	XIMPL (34)	Main oxidizer turbine admission reduced	Flag			MAIND	Output
51	XIMPL (35)	Fuel pump rpm reduced by pump routine	Flag			MAIND	Output
52	XIMPL (36)	Oxidizer pump rpm reduced by pump routine	Flag			MAIND	Output
53	XIMPL (37)	NCU					
54	XIMPL (38)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
55	XIMPL (39)	NCU					
56	XIMPL (40)	NCU					
57	XIMPL (41)	NCU					
58	XIMPL (42)	NCU					
59	XIMPL (43)	NCU					
60	XIMPL (44)	Main oxidizer turbine iterations exceeded	Flag			MAIND	Output
61	XIMPL (45)	Main fuel turbine iterations exceeded	Flag			MAIND	Output
62	XIMPL (46)	Fuel pump iterations exceeded	Flag			MAIND	Output
63	XIMPL (47)	Oxidizer pump iterations exceeded	Flag			MAIND	Output
64	XIMPL (48)	Nozzle coolant bulk temperature exceeded	Flag			MAIND	Output
65	XIMPL (49)	Combustor coolant max. bulk temperature exceeded	Flag			MAIND	Output
66	XIMPL (50)	Kick pump impeller tip width minimum violated	Flag			MAIND	Output
67	XIMPL (51)	Kick pump inlet/exit diameter ratio max. violated	Flag			MAIND	Output
68	XIMPL (52)	Kick pump impeller stage specific speed max. exceeded	Flag			MAIND	Output
69	XIMPL (53)	Kick pump impeller tip diameter min. violated	Flag			MAIND	Output
70	XIMPL (54)	NCU					
71	XIMPL (55)	Oxidizer turbine hub/tip ratio too low	Flag			MAIND	Output
72	XIMPL (56)	Fuel turbine hub/tip ratio too low	Flag			MAIND	Output
73	XIMPL (57)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
74	XIMPL (58)	NCU					
75	XIMPL (59)	GG Pc too high	Flag			MAIND	Output
76	XIMPL (60)	Main turbine required flow rates >available	Flag			MAIND	Output
$\boxed{77}$	XEXPLL (1)	Lower limit for main fuel pump speed	rpm	5000		EXPL	Input
$\boxed{78}$	XEXPLL (2)	Lower limit for main oxidizer pump speed	rpm	5000		EXPL	Input
$\boxed{79}$	XEXPLL (3)	Lower limit for main fuel turbine admission fraction	None	.9	10	EXPL	Input
$\boxed{80}$	XEXPLL (4)	Lower limit for main oxidizer turbine admission fraction	None	.9	10	EXPL	Input
$\boxed{81}$	XEXPLL (5)	Lower limit for $\dot{W}c/\dot{W}t$ (combustor coolant/ total fuel)	None	.49	11	EXPL	Input
$\boxed{82}$	XEXPLL (6)	Lower limit for main turbine pressure ratio	None	1.15		EXPL	Input
83	XEXPLL (7)	NCU					
$\boxed{84}$	XEXPLU (1)	Upper limit for main fuel pump speed	rpm	50,000		EXPL	Input
$\boxed{85}$	XEXPLU (2)	Upper limit for main oxidizer pump speed	rpm	50,000		EXPL	Input
$\boxed{86}$	XEXPLU (3)	Upper limit for main fuel turbine admission	None	1.		EXPL	Input
$\boxed{87}$	XEXPLU (4)	Upper limit for main oxidizer turbine admission	None	1.		EXPL	Input
$\boxed{88}$	XEXPLU (5)	Upper limit for $\dot{W}c/\dot{W}t$ (combustor coolant/ total fuel)	None	.51	11	EXPL	Input
$\boxed{89}$	XEXPLU (6)	Upper limit for main turbine pressure ratio	None	5		EXPL	Input
90	XEXPLU (7)	NCU					
91	XEXPLU (8)	NCU					
92	XEXPLU (9)	NCU					
93	XEXPLU (10)	OPT error flag, J	None	0		IMPL	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
94	ALPHA	Optimizer reflection factor (must be >1.0)	None	1.3	12	OPT	Input
95	TOL	Optimizer termination tolerance	None	.0001	12	OPT	Input
96	TURBIN (1)	Turbine size = 0: ≈2" in diameter = 1: >3" in diameter	Flag	1		TRBN1D	Input
97	TURBIN (2)	Main turbine max. tip speed	ft/sec	1850		TRBN1D	Input
98	TURBIN (3)	Minimum blade height for main turbines	inches	.25		TRBN1D	Input
99	TURBIN (4)	Maximum annulus area x speed squared	in^2-rpm	4×10^{10}		TRBN1D	Input
100	TURBIN (5)	Main fuel turbine type 1 = 1-row impulse 2 = 2-row velocity compounded 3 = 1-stage 50% reaction 4 = 2-stage impulse 5 = 2-stage reaction	Flag	4		TRBN1D	Input
101	TURBIN (6)	Main oxidizer turbine 1 = 1-row impulse 2 = 2-row velocity compounded 3 = 1-stage 50% reaction 4 = 2-stage impulse 5 = 2-stage reaction	Flag	4		TRBN1D	Input
102	TURBIN (7)	Main turbine minimum pitch diameter	inches	2		TRBN1D	Input
103	TURBIN (8)	Main turbine max. hub/tip ratio	None	.9		TRBN1D	Input
104	TURBIN (9)	Main fuel turbine shaft sizing 0 = shaft based on critical speed 1 = shaft based on torque	Flag	1	8	PUMPD	Input
105	TURBIN (10)	Main oxidizer turbine shaft sizing 0 = shaft based on critical speed 1 = shaft based on torque	Flag	1	8	PUMPD	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
106	TURBIN (11)	Fuel turbine inlet temperature	°R	2000		TRBN1D	Input
107	TURBIN (12)	Oxidizer turbine inlet temperature	°R	2000		TRBN1D	Input
108	TURBIN (13)	Main turbine min. hub/tip ratio	None	.6		MAIND	Input
109	TURBIN (14)	NCU					
110	TURBIN (15)	NCU					
111	PUMPIN (1)	Engine inlet fuel pressure	psia	30		DELTAD	Input
112	PUMPIN (2)	Engine inlet oxidizer pressure	psia	30		DELTAD	Input
113	PUMPIN (3)	Engine inlet fuel NPSP	psi	15.3		MAIND	Input
114	PUMPIN (4)	Engine inlet oxidizer NPSP	psi	15.3		MAIND	Input
115	PUMPIN (5)	Fuel kick pump flag (value is number of stages)	Flag	0		MAIND	Input
116	PUMPIN (6)	Oxid. kick pump flag (value is number of stages)	Flag	1		MAIND	Input
117	PUMPIN (7)	Number of main fuel pump centrifugal stages	None	3		MAIND	Input
118	PUMPIN (8)	Number of main oxidizer pump centrifugal stages	None	1		MAIND	Input
119	PUMPIN (9)	Fuel pump leakage	Fraction	0		IMPULS	Input
120	PUMPIN (10)	Oxidizer pump leakage	Fraction	0		IMPULS	Input
121	PUMPIN (11)	Main fuel pump inducer flow coefficient	None	.1		MAIND	Input
122	PUMPIN (12)	Main oxidizer pump inducer flow coefficient	None	.1		MAIND	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
123	PUMPIN (13)	> 0 Constrain main pumps to available NPSH	Flag	0		MAIND	Input
124	PUMPIN (14)	NCU					
125	PUMPIN (15)	Main fuel pump inducer inlet hub/tip ratio	Fraction	.35		MAIND	Input
126	PUMPIN (16)	Main oxidizer pump inducer inlet hub/tip ratio	Fraction	.35		MAIND	Input
127	PUMPIN (17)	NCU					
128	PUMPIN (18)	NCU					
129	PUMPIN (19)	Flag: = 1 oxidizer pump is double-entry = 0 oxidizer pump is not double-entry	Flag	0	13	MAIND	Input
130	PUMPIN (20)	NCU					
131	DELTAP (1)	Delta P/upstream pressure: Line	None	.005		DELTAD	Input
132	DELTAP (2)	Valve, on/off	None	.01		DELTAD	Input
133	DELTAP (3)	Valve, liq. control	None	.05		DELTAD	Input
134	DELTAP (4)	Valve, gas control	None	.1		DELTAD	Input
135	DELTAP (5)	Injector, liquid	None	.15		DELTAD	Input
136	DELTAP (6)	Injector, gas	None	.08		DELTAD	Input
137	DELTAP (7)	NCU					
138	DELTAP (8)	NCU					
139	DELTAP (9)	NCU					
140	DELTAP (10)	GG cycle turbine exit pressure	psia	30		CSUBF	Input

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
141	DELTAP (11)	Combustor coolant flow rate	lb/sec			MAIND	Output
142	DELTAP (12)	Nozzle coolant flow rate	lb/sec			MAIND	Output
143	DELTAP (13)	Combustor coolant jacket delta P	psi			REGEN	Output
144	DELTAP (14)	Nozzle coolant jacket delta P	psi			REGEN	Output
145	DELTAP (16)	$Q_{NBL}/Q_{combustor}$	None	.2	14	REGEN	Input
146	DELTAP (16)	Thrust chamber cycle life	None	100		REGEN	Input
147	DELTAP (17)	NCU					
148	DELTAP (18)	NCU					
149	DELTAP (19)	NCU					
150	DELTAP (20)	NCU					
$\boxed{151}$	GUESS (1)	Main fuel pump speed initial guess	rpm	15000		MAIND	Input
$\boxed{152}$	GUESS (2)	Main oxidizer pump speed initial guess	rpm	6000		MAIND	Input
$\boxed{153}$	GUESS (3)	Main fuel turbine admission initial guess	None	.999		MAIND	Input
$\boxed{154}$	GUESS (4)	Main oxidizer turbine admission initial guess	None	.999		MAIND	Input
$\boxed{155}$	GUESS (5)	$\dot{W}_c/\dot{W}_t$ (combustor coolant/total fuel) initial guess	None	.5	11	MAIND	Input
$\boxed{156}$	GUESS (6)	Main fuel turbine pressure ratio initial guess	None	1.79		MAIND	Input
157	TRBOUT (1)	Fuel turbine exit temperature	°R			TRBN1D	Output
158	TRBOUT (2)	Oxidizer turbine exit temperature	°R			TRBN1D	Output
159	TRBOUT (3)	Oxidizer turbopump weight	Lb			MAIND	Output
160	TRBOUT (4)	Fuel turbopump weight	Lb			MAIND	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
161	TRBOUT (5)	NCU					
162	TRBOUT (6)	NCU					
163	SPACE (1)	Termination tolerance (for program usage)	None			MAIND	PGM
164	SPACE (2)	Max. nozzle coolant bulk temperature	°R	2000		MAIND	Input
165	SPACE (3)	Max. combustor coolant bulk temperature	°R	2000		MAIND	Input
$\boxed{166}$	SPACE (4)	C* efficiency	None	.98	16	NCU	Input
167	SPACE (5)	Kinetic efficiency (0 if table is input)	None	0	16	CSIS	Input
168	SPACE (6)	γ for $P_{nozzle\ exit}$ calculation	None	1.139		IMPULS	Input
169	SPACE (7)	Preburner fuel inlet temp or expander cycle turbine inlet temp	°R			TEMP	Output
170	SPACE (8)	NCU					
171	SPACE (9)	Combustor exit enthalpy	Btu/lb			REGEN	Output
172	SPACE (10)	Nozzle exit enthalpy	Btu/lb			REGEN	Output
173	SPACE (11)	PB or exp cycle fuel inlet enthalpy	Btu/lb			REGEN	Output
174	SPACE (12)	NCU					
175	SPACE (13)	NCU					
176	SPACE (14)	NCU					
177	SPACE (15)	NCU					
178	SPACE (16)	NCU					
179	SPACE (17)	NCU					
180	SPACE (18)	NCU					
181	SPACE (19)	NCU					
182	SPACE (20)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
183	SPACE (21)	NCU					
184	SPACE (22)	NCU					
185	SPACE (23)	NCU					
186	SPACE (24)	Flag: > 0 use following user input:	Flag	0		REGEN	Input
187	SPACE (25)	Combustor coolant jacket delta P	psi	0		REGEN	Input
188	SPACE (26)	Nozzle coolant jacket delta P	psi	0		REGEN	Input
189	SPACE (27)	Combustor heat load	Btu/sec	0		REGEN	Input
190	SPACE (28)	Nozzle heat load	Btu/sec	0		REGEN	Input
191	PCTLNG	Nozzle percent length	Fraction	.9		IMPULS	Input
192	ETASEC	GG flow I_s efficiency	None	.982		IMPULS	Input
193	DFLG	Dump coolant flow	lb/sec	0		IMPULS	Input
194	ISDUMP	Dump coolant I_s	sec	0		IMPULS	Input
195	TAU	$\dot{W}s/\dot{W}p$ (turbine exhaust flow/thrust chamber flow)	None			IMPULS	Output
196	ENGFUL	Engine fuel flow	lb/sec			IMPULS	Output
197	ENGOX	Engine oxidizer flow	lb/sec			IMPULS	Output
198	PBFFLO	PB or GG fuel flow	lb/sec			IMPULS	Output
199	PBOFLO	PB or GG oxidizer flow	lb/sec			IMPULS	Output
200	AT	Nozzle throat area	in^2			IMPULS	Output
201	CF	Nozzle C_f	None			IMPULS	Output
202	FP	Thrust chamber thrust	lb			IMPULS	Output
203	TCMR	Thrust chamber mixture ratio	None			IMPULS	Output
204	TCIS	Thrust chamber I_s	sec			CSIS	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
205	ISSEC	Secondary (turbine exhaust) I_s	sec			IMPULS	Output
206	PROP (1)	Fuel density	lb/ft^3			PRPRP	Output
207	PROP (2)	Oxidizer density	lb/ft^3			PRPRP	Output
208	PROP (3)	Fuel molecular weight	g/mole			PRPRP	Output
209	PROP (4)	Oxidizer molecular weight	g/mole			PRPRP	Output
210	PROP (5)	Fuel engine inlet heat of formation	Kcal/gm -mole			PRPRP	Output
211	PROP (6)	Oxidizer engine inlet heat of formaion	Kcal/gm -mole			PRPRP	Output
212	PROP (7)	Fuel NPSH/$C_m^2/2g$	None			PRPRP	Output
213	PROP (8)	Oxidizer NPSH/$C_m^2/2g$	None			PRPRP	Output
214	PROP (9)	Fuel engine inlet enthalpy	Btu/lb			PRPRP	Output
215	PROP (10)	NCU					
216	PROP (11)	NCU					
217	PROP (12)	NCU					
218	PROP (13)	NCU					
219	PROP (14)	NCU					
220	PROP (15)	NCU					
221	PRES (1)	Oxidizer engine inlet pressure	psia			DELTAD	Output
222	PRES (2)	Oxidizer engine inlet NPSH	ft			MAIND	Output
223	PRES (3)	Oxidizer main turbine pressure ratio	None			DELTAD	Output
224	PRES (4)	Oxidizer main pump inlet pressure	psia			DELTAD	Output
225	PRES (5)	Oxidizer main pump discharge pressure	psia			DELTAD	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
226	PRES (6)	Preburner branch point pressure (oxidizer)	psia			DELTAD	Output
227	PRES (7)	Oxidizer main injector inlet pressure	psia			DELTAD	Output
228	PRES (8)	Fuel engine inlet pressure	psia			DELTAD	Output
229	PRES (9)	Fuel engine inlet NPSH	ft			MAIND	Output
230	PRES (10)	Fuel main turbine pressure ratio	None			PROCES	Output
231	PRES (11)	Fuel main pump inlet pressure	psia			DELTAD	Output
232	PRES (12)	Fuel main pump discharge pressure	psia			DELTAD	Output
233	PRES (13)	Cooling jacket inlet pressure	psia			DELTAD	Output
234	PRES (14)	Combustor jacket outlet pressure	psia			DELTAD	Output
235	PRES (15)	Fuel preburner branch point pressure	psia			DELTAD	Output
236	PRES (16)	Nozzle jacket outlet pressure	psia			DELTAD	Output
237	PRES (17)	Oxidizer kick-pump discharge pressure	psia			DELTAD	Output
238	PRES (18)	Fuel kick-pump discharge pressure	psia			DELTAD	Output
239	PRES (19)	NCU					
240	PRES (20)	Oxidizer preburner Pc or GG Pc	psia			DELTAD	Output
241	PRES (21)	Fuel preburner Pc or maximum GG Pc	psia			PROCES	Output
242	PRES (22)	Hot gas main oxidizer turbine discharge pressure	psia			DELTAD	Output
243	PRES (23)	Hot gas main fuel turbine discharge pressure	psia			DELTAD	Output
244	PRES (24)	Hot fuel-rich gas main injector inlet pressure	psia			DELTAD	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
245	PRES (25)	Chamber pressure	psia			MAIND	Output
246	PRES (26)	Hot oxidizer-rich gas main injector inlet pressure	psia			NCU	Output
247	PRES (27)	NCU					
248	PRES (28)	NCU					
249	PRES (29)	Nozzle exit pressure	psia			IMPULS	Output
250	PRES (30)	Nozzle exit wall pressure	psia			IMPULS	Output
251	HEAT (1)	Combustor heat load	Btu/sec			REGEN	Output
252	HEAT (2)	Nozzle heat load	Btu/sec			REGEN	Output
253	HEAT (3)	Nozzle coolant exit temperature	°R			TEMP	Output
254	HEAT (4)	Combustor coolant exit temperature	°R			TEMP	Output
255	PMPOX (1)	Main oxidizer pump inducer inlet flow velocity	ft/sec			PMPCNV	Output
256	PMPOX (2)	Main oxidizer pump inducer tip speed	ft/sec			PMPCNV	Output
257	PMPOX (3)	Main oxidizer pump inducer inlet flow coefficient	None			PMPCNV	Output
258	PMPOX (4)	NCU	None				
259	PMPOX (5)	Main oxidizer pump inducer diameter	inches			PMPCNV	Output
260	PMPOX (6)	Main oxidizer pump inducer inlet flow area	in^2			PMPCNV	Output
261	PMPOX (7)	NCU				PMPCNV	

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
262	PMPOX (8)	NCU					
263	PMPOX (9)	NCU					
264	PMPOX (10)	NCU					
265	PMPOX (11)	Main oxidizer pump inducer required NPSH	ft			PMPCNV	Output
266	PMPOX (12)	NCU					
267	PMPOX (13)	Main oxidizer pump impeller tip speed	ft/sec			PUMPD	Output
268	PMPOX (14)	NCU					
269	PMPOX (15)	Main oxidizer pump impeller head coefficient	None			PUMPD	Output
270	PMPOX (16)	Main oxidizer pump impeller diameter	in.			PUMPD	Output
271	PMPOX (17)	Main oxidizer pump impeller tip width	in.			PUMPD	Output
272	PMPOX (18)	Main oxidizer pump inlet/exit diameter ratio	None			PUMPD	Output
273	PMPOX (19)	Main oxidizer pump impeller stage specific speed	$\frac{rpm\sqrt{gpm}}{ft^{3/4}}$			PUMPD	Output
274	PMPOX (20)	Main oxidizer pump impeller head rise/stage	ft			PUMPD	Output
275	PMPOX (21)	NCU	None				
276	PMPOX (22)	Main oxidizer pump overall efficiency	None			PUMPD	Output
277	PMPOX (23)	Main oxidizer pump overall horsepower	HP			PUMPD	Output
278	PMPOX (24)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
279	PMPFUL (1)	Main fuel pump inducer inlet flow velocity	ft/sec			PMPCNV	Output
280	PMPFUL (2)	Main fuel pump inducer tip speed	ft/sec			PMPCNV	Output
281	PMPFUL (3)	Main fuel pump inducer inlet flow coefficient	None			PMPCNV	Output
282	PMPFUL (4)	NCU					
283	PMPFUL (5)	Main fuel pump inducer diameter	inches			PMPCNV	Output
284	PMPFUL (6)	Main fuel pump inducer inlet flow area	$in.^2$			PMPCNV	Output
285	PMPFUL (7)	NCU					
286	PMPFUL (8)	NCU					
287	PMPFUL (9)	NCU					
288	PMPFUL (10)	NCU					
289	PMPFUL (11)	Main fuel pump inducer required NPSH	ft			PMPCNV	
290	PMPFUL (12)	NCU					
291	PMPFUL (13)	Main fuel pump impeller tip speed	ft/sec			PUMPD	Output
292	PMPFUL (14)	NCU					
293	PMPFUL(15)	Main fuel pump impeller head coefficient	None			PUMPD	Output
294	PMPFUL (16)	Main fuel pump impeller diameter	inches			PUMPD	Output
295	PMPFUL (17)	Main fuel pump impeller tip width	inches			PUMPD	Output
296	PMPFUL (18)	Main fuel pump inlet/exit diameter ratio	None			PUMPD	Output
297	PMPFUL (19)	Main fuel pump impeller stage specific speed	$\frac{rpm\sqrt{gpm}}{ft^{3/4}}$			PUMPD	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
298	PMPFUL (20)	Main fuel pump impeller head rise/stage	feet			PUMPD	Output
299	PMPFUL (21)	NCU					
300	PMPFUL (22)	Main fuel pump overall efficiency	None			PUMPD	Output
301	PMPFUL (23)	Main fuel pump overall horsepower	HP			PUMPD	Output
302	PMPFUL (24)	NCU					
303	DRIVE (1)	Fuel turbine mixture ratio	None			PROCES	Output
304	DRIVE (2)	Fuel turbine gas molecular weight	g/mole			PROCES	Output
305	DRIVE (3)	Fuel turbine gas isentropic exponent	None			PROCES	Output
306	DRIVE (4)	Fuel turbine gas process specific heat	$\frac{btu}{lb-R}$			PROCES	Output
307	DRIVE (5)	Oxidizer kick pump flowrate	lb/sec				Output
308	DRIVE (6)	Fuel kick pump flowrate	lb/sec				Output
309	DRIVE (7)	Nozzle extension dump coolant flowrate	lb/sec			IMPULS	Output
310	DRIVE (8)	Oxidizer turbine gas isentropic exponent	None			PROCES	Output
311	DRIVE (9)	Oxidizer turbine gas process specific heat	$\frac{btu}{lb-R}$			PROCES	Output
312	DRIVE (10)	Oxidizer turbine inlet temperature	°R			MAIND	Output
313	DRIVE (11)	Fuel turbine inlet temperature	°R			MAIND	Output
314	DRIVE (12)	NCU					
315	DRIVE (13)	Oxidizer turbine gas molecular weight	g/mole			PROCES	Output
316	DRIVE (14)	Oxidizer turbine mixture ratio	None			PROCES	Output
317	DRIVE (15)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
318	TRBOX (1)	Main oxidizer turbine efficiency	None			TRBN1D	Output
319	TRBOX (2)	Main oxidizer turbine pitch diameter	inches			TRBN1D	Output
320	TRBOX (3)	Main oxidizer turbine flowrate	lb/sec			TRBN1D	Output
321	TRBOX (4)	Main oxidizer turbine horsepower	HP			TRBN1D	Output
322	TRBOX (5)	Main oxidizer turbine first row (stage) blade height	inches			TRBN1D	Output
323	TRBOX (6)	Main oxidizer turbine second row (stage) blade height	inches			TRBN1D	Output
324	TRBOX (7)	Main oxidizer turbine velocity ratio	None			TRBN1D	Output
325	TRBOX (8)	Main oxidizer turbine tip speed	ft/sec			TRBN1D	Output
326	TRBOX (9)	Main oxidizer turbine annulus area x speed squared	in^2-rpm^2			TRBN1D	Output
327	TRBOX (10)	Number of iterations for oxidizer turbine routine convergence	None			TRBN1D	Output
328	TRBOX (11)	Bearing DN for main oxidizer turbopump	mm·rpm			TRBN1D	Output
329	TRBFUL (1)	Main fuel turbine efficiency	None			TRBN1D	Output
330	TRBFUL (2)	Main fuel turbine pitch diameter	inches			TRBN1D	Output
331	TRBFUL (3)	Main fuel turbine flowrate	lb/sec			TRBN1D	Output
332	TRBFUL (4)	Main fuel turbine horsepower	HP			TRBN1D	Output
333	TRBFUL (5)	Main fuel turbine first row (stage) blade height	inches			TRBN1D	Output
334	TRBFUL (6)	Main fuel turbine second row (stage) blade height	inches			TRBN1D	Output
335	TRBFUL (7)	Main fuel turbine velocity ratio	None			TRBN1D	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
336	TRBFUL (8)	Main fuel turbine tip speed	ft/sec			TRBN1D	Output
337	TRBFUL (9)	Main fuel turbine annulus area x speed squared	in^2-rpm^2			TRBN1D	Output
338	TRBFUL (10)	Number of iterations for fuel turbine routine convergence	None			TRBN1D	Output
339	TRBFUL (11)	Bearing DN for main fuel turbine	mm x rpm			TRBN1D	Output
340	TURPMP (1)	Minimum oxidizer boost pump delta p	psi			MAIND	Output
341	TURPMP (2)	Minimum fuel boost pump delta p	psi			MAIND	Output
342	TURPMP (3)	Oxidizer pump flow	gpm			MAIND	Output
343	TURPMP (4)	Fuel pump flow	gpm			MAIND	Output
344	TURPMP (5)	Oxidizer turbine hub/tip ratio	None			MAIND	Output
345	TURPMP (6)	Fuel turbine hub/tip ratio	None			MAIND	Output
346	TURPMP (7)	NCU					
347	H2BSTO (1)	NCU					
348	H2BSTO (2)	NCU					
349	H2BSTO (3)	NCU					
350	H2BSTO (4)	NCU					
351	H2BSTO (5)	NCU					
352	H2BSTO (6)	NCU					
353	H2BSTO (7)	NCU					
354	H2BSTO (8)	NCU					
355	H2BSTO (9)	NCU					
356	H2BSTO (10)	NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
357	H2BSTO (11)	NCU					
358	H2BSTF (1)	NCU					
359	H2BSTF (2)	NCU					
360	H2BSTF (3)	NCU					
361	H2BSTF (4)	NCU					
362	H2BSTF (5)	NCU					
363	H2BSTF (6)	NCU					
364	H2BSTF (7)	NCU					
365	H2BSTF (8)	NCU					
366	H2BSTF (9)	NCU					
367	H2BSTF (10)	NCU					
368	H2BSTF (11)	NCU					
369	X (1,1)	Optimum main fuel pump speed	rpm			OPT	Output
370	X (2,1)	Location used by optimizer	None			OPT	PGM
371	X(3,1)	Location used by optimizer	None			OPT	PGM
372	X (4,1)	Location used by optimizer	None			OPT	PGM
373	X (5,1)	Location used by optimizer	None			OPT	PGM
374	X (6,1)	Location used by optimizer	None			OPT	PGM
375	X (7,1)	Location used by optimizer	None			OPT	PGM
376	X (8,1)	Location used by optimizer	None			OPT	PGM
377	X (9,1)	Location used by optimizer	None			OPT	PGM
378	X (10,1)	Location used by optimizer	None			OPT	PGM

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
379	X (1,2)	Optimum Main Oxidizer Pump Speed	rpm			OPT	Output
380	X (2,2)	Location used by optimizer	None			OPT	PGM
381	X (3,2)	Location used by optimizer	None			OPT	PGM
382	X (4,2)	Location used by optimizer	None			OPT	PGM
383	X (5,2)	Location used by optimizer	None			OPT	PGM
384	X (6,2)	Location used by optimizer	None			OPT	PGM
385	X (7,2)	Location used by optimizer	None			OPT	PGM
386	X (8,2)	Location used by optimizer	None			OPT	PGM
387	X (9,2)	Location used by optimizer	None			OPT	PGM
388	X (10,2)	Location used by optimizer	None			OPT	PGM
389	X (1, 3)	Optimum main fuel turbine admission	None			OPT	Output
390	X (2,3)	Location used by optimizer	None			OPT	PGM
391	X (3,3)	Location used by optimizer	None			OPT	PGM
392	X (4,3)	Location used by optimizer	None			OPT	PGM
393	X (5,3)	Location used by optimizer	None			OPT	PGM
394	X (6,3)	Location used by optimizer	None			OPT	PGM
395	X (7,3)	Location used by optimizer	None			OPT	PGM
396	X (8,3)	Location used by optimizer	None			OPT	PGM
397	X (9,3)	Location used by optimizer	None			OPT	PGM
398	X (10,3)	Location used by optimizer	None			OPT	Output
399	X (1, 4)	Optimum main oxidizer turbine admission	None			OPT	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
400	X (2,4)	Location used by optimizer	None			OPT	PGM
401	X (3,4)	Location used by optimizer	None			OPT	PGM
402	X (4,4)	Location used by optimizer	None			OPT	PGM
403	X (5,4)	Location used by optimizer	None			OPT	PGM
404	X (6,4)	Location used by optimizer	None			OPT	PGM
405	X (7,4)	Location used by optimizer	None			OPT	PGM
406	X (8,4)	Location used by optimizer	None			OPT	PGM
407	X (9,4)	Location used by optimizer	None			OPT	PGM
408	X (10,4)	Location used by optimizer	None			OPT	PGM
409	X (1,5)	Optimum coolant flow split $\dot{W}$comb/$\dot{W}$nozz	None			OPT	Output
410	X (2,5)	Location used by optimizer	None			OPT	PGM
411	X (3,5)	Location used by optimizer	None			OPT	PGM
412	X (4,5)	Location used by optimizer	None			OPT	PGM
413	X (5,5)	Location used by optimizer	None			OPT	PGM
414	X (6,5)	Location used by optimizer	None			OPT	PGM
415	X (7,5)	Location used by optimizer	None			OPT	PGM
416	X (8,5)	Location used by optimizer	None			OPT	PGM
417	X (9,5)	Location used by optimizer	None			OPT	PGM
418	X (10,5)	Location used by optimizer	None			OPT	PGM
419	X (1,6)	Optimum main fuel turbine pressure ratio	None			OPT	Output
420	X (2,6)	Location used by optimizer	None			OPT	PGM
421	X (3,6)	Location used by optimizer	None				

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
422	X (4,6)	Location used by optimizer	None			OPT	PGM
423	X (5,6)	Location used by optimizer	None			OPT	PGM
424	X (6,6)	Location used by optimizer	None			OPT	PGM
425	X (7,6)	Location used by optimizer	None			OPT	PGM
426	X (8,6)	Location used by optimizer	None			OPT	PGM
427	X (9,6)	Location used by optimizer	None			OPT	PGM
428	X (10,6)	Location used by optimizer	None			OPT	PGM
429	WFUEL	Thrust chamber fuel flowrate	lb/sec			IMPULS	Output
430	WOX	Thrust chamber oxidizer flowrate	lb/sec			IMPULS	Output
431	WAVAIL	Available main turbine flowrate	lb/sec			MAIND	Output
432	WREQD	Required main turbine flowrate	lb/sec			MAIND	Output
433	WAVALB	NCU					
434	WREQDB	NCU					
435	FBY	Main turbine fuel bypass	None			MAIND	Output
436	FBYBST	NCU					
437	XITER	Total number of optimizer iterations	NONE			MAIND	Output
438	SOLVEW	Flowrate minimization	Flag			MAIND	PGM
439	OBJECT	Object function	None			MAIND	PGM
440	PMPKCK (1)	Oxidizer kick pump inlet flow velocity	ft/sec			PUMPD	Output
441	PMPKCK (2)	Oxidizer kick pump tip speed	ft/sec			PUMPD	Output
442	PMPKCK (3)	Oxidizer kick pump inlet flow coefficient	None			PUMPD	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
443	PMPKCK (4)	Oxidizer kick pump head coefficient	None			PUMPD	Output
444	PMPKCK (5)	Oxidizer kick pump diameter	inches			PUMPD	Output
445	PMPKCK (6)	Oxidizer kick pump tip width	inches			PUMPD	Output
446	PMPKCK (7)	Oxidizer kick pump inlet/exit diameter	None			PUMPD	Output
447	PMPKCK (8)	Oxidizer kick pump specific speed	$\frac{\text{rpm gpm}}{\text{ft } 3/4}$			PUMPD	Output
448	PMPKCK (9)	Oxidizer kick pump head rise	feet			PUMPD	Output
449	PMPKCK (10)	Oxidizer kick pump efficiency	None			PUMPD	Output
450	PMPKCK (11)	Oxidizer kick pump inlet flow area	$in.^2$			PUMPD	Output
451	PMPKCK (12)	Oxidizer kick pump horsepower	HP			PUMPD	Output
452	PMPKCK (13)	Oxidizer kick pump delivered NPSH	feet			PUMPD	Output
453	HF (1)	Fuel preburner inlet fuel heat of formation	Kcal/ mole			REGEN	Output
454	HF (2)	Oxidizer preburner inlet fuel heat of formation	Kcal/ mole			REGEN	Output
455	PERF (1)	Engine specific impulse	sec			IMPULS	Output
456	PERF (2)	Thrust chamber C*	ft/sec			CSIS	Output
457	PERF (3)	Sea level specific impulse	sec			IMPULS	Output
458	PERF (4)	Thrust chamber theoretical specific impulse	sec			CSIS	Output
459	PERF (5)	Thrust chamber theoretical C*	ft/sec			CSIS	Output
460	PBMR1	Fuel preburner mixture ratio	None			PROCES	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
461	PBMR2	Oxidizer preburner mixture ratio	None			PROCES	Output
462	HFTC	Thrust chamber inlet fuel heat of formation	Kcal/ mole			REGEN	Output
463	EFFTDK (1)	Thrust chamber kinetic efficiency	None			KINEFF	Output
464	EFFTDK (2)	Thrust chamber C* efficiency	None			CSIS	Output
465	EFFTDK (3)	Thrust chamber divergence efficiency	None			CSIS	Output
466	EFFTDK (4)	Thrust chamber boundary layer loss	None			CSIS	Output
467	EFFTDK (5)	Thrust chamber boundary layer efficiency	None			CSIS	Output
468	MRPBO	Overall preburner mixture ratio	None			MAIND	Output
469	FSL	Sea level thrust	Lb			IMPULS	Output
470	BETAF1	NCU					
471	HYFTRB (1)	NCU					
472	HYFTRB (2)	NCU					
473	HYFTRB (3)	NCU					
474	HYFTRB (4)	NCU					
475	HYFTRB (5)	NCU					
476	HYFTRB (6)	NCU					
477	HYFTRB (7)	NCU					
478		NCU					
479		NCU					
480		NCU					
481		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
482		NCU					
483		NCU					
484		NCU					
485		NCU					
486		NCU					
487		NCU					
488		NCU					
489		NCU					
490		NCU					
491		NCU					
492		NCU					
493		NCU					
494		NCU					
495		NCU					
496		NCU					
497		NCU					
498		NCU					
499		NCU					
500		NCU					
501	FULKCK (1)	Fuel kick pump inlet flow velocity	ft/sec			PUMPD	Output
502	FULKCK (2)	Fuel kick pump tip speed	ft/sec			PUMPD	Output

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
503	FULKCK (3)	Fuel kick pump inlet flow coefficient	None	0		PUMPD	Output
504	FULKCK (4)	Fuel kick pump head coefficient	None	0		PUMPD	Output
505	FULKCK (5)	Fuel kick pump diameter	inches	0		PUMPD	Output
506	FULKCK (6)	Fuel kick pump tip width	inches	0		PUMPD	Output
507	FULKCK (7)	Fuel kick pump inlet/exit diameter ratio	None	0		PUMPD	Output
508	FULKCK (8)	Fuel kick pump specific speed	$\frac{rpm}{ft}\ \frac{gpm}{3/4}$	0		PUMPD	Output
509	FULKCK (9)	Fuel kick pump head rise	feet	0		PUMPD	Output
510	FULKCK (10)	Fuel kick pump efficiency	None	0		PUMPD	Output
511	FULKCK (11)	Fuel kick pump inlet flow area	in^2	0		PUMPD	Output
512	FULKCK (12)	Fuel kick pump horsepower	HP	0		PUMPD	Output
513	FULKCK (13)	Fuel kick pump delivered NPSH	feet	0		PUMPD	Output
514		NCU					
515		NCU					
516		NCU					
517		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
518		NCU					
519		NCU					
520		NCU					
521		NCU					
522		NCU					
523		NCU					
524		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
525		NCU					
526		NCU					
527		NCU					
528		NCU					
529		NCU					
530		NCU					
531		NCU					
532		NCU					
533		NCU					
534		NCU					
535		NCU					
536		NCU					
537		NCU					
538		NCU					
539		NCU					
540		NCU					
541		NCU					
542		NCU					
543		NCU					
544		NCU					
545		NCU					
546		NCU					
547		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
548		NCU					
549		NCU					
550		NCU					
551		NCU					
552		NCU					
553		NCU					
554		NCU					
555		NCU					
556		NCU					
557		NCU					
558		NCU					
559		NCU					
560		NCU					
561		NCU					
562		NCU					
563		NCU					
564		NCU					
565		NCU					
566		NCU					
567		NCU					
568		NCU					
569		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
570		NCU					
571		NCU					
572		NCU					
573		NCU					
574		NCU					
575		NCU					
576		NCU					
577		NCU					
578		NCU					
579		NCU					
580		NCU					
581		NCU					
582		NCU					
583		NCU					
584		NCU					
585		NCU					
586		NCU					
587		NCU					
588		NCU					
589		NCU					
590		NCU					
591		NCU					

ENGINE INPUT/OUTPUT BLOCK

LOCATION	NAME	DESCRIPTION	UNITS	DEFAULT VALUE	NOTES	DEFINED OR USED BY	INPUT OUTPUT
592		NCU					
593		NCU					
594		NCU					
595		NCU					
596		NCU					
597		NCU					
598		NCU					
599		NCU					
600		NCU					

COMMON BLOCK NOTES

1 - Location 5, Fuel bypass fraction: This input specifies the fraction of the total fuel flow unavailable to the preburners or turbines. It is meaningful only for staged combustion and expander cycles.

2 - Location 9, Print flag: The Univac Postmortem Dump (PMD) processor is a useful tool for finding the cause of fatal mathematical errors. It's use requires that the program output be printed at an interactive terminal rather than a disc file. This flag is intended to save time by suppressing the initial portion of the printout which summarizes the options selected.

3 - Location 10, Cooling circuit flag: This flag specifies a series cooling circuit, with all the coolant passing through the combustor and nozzle in series, or a parallel circuit, with the flow split between the combustor and nozzle and recombining at the coolant jacket exits.

4 - Location 11, Minimization objective: The program offers three optimization options; (1) chamber pressure maximization, for staged combustion and expander cycles, (2) fuel pump discharge pressure minimization, for staged combustion and expander cycles when the user wishes to specify the chamber pressure, and (3) turbine flow minimization, for gas generator cycles.

5 - Location 12, Initial guess flag: When several cases are being run together, the initial guess flag provides a means of insuring in advance that the initial guesses are acceptable. If the flag is set to 2.0, a single line will be printed for each case. A full printout is provided if the flag is set to 1.0.

6 - Location 13, Maximum number of optimizer iterations: This limit is intended to avoid excessive run times by limiting the total number of program iterations. The number of iterations printed during program execution is the number of successful iterations and will be less than the total, which includes those cases violating implicit constraints.

7 - Location 16, Coolant jacket bypass fraction: This input specifies the fraction of the total fuel flow unavailable for thrust chamber cooling.

8 - Locations 21-22, 25-28, & 104-105, Pump DN and tip speed limits: These limits depe on a number of factors, including propellant combination, materials, turbopump configuration, life requirements and method of construction. The bearing DN is the product of the shaft diameter and rotating speed. Two options are provided for calculating this value (locations 104 & 105) depending on how the shaft is sized. If the turbopump bearings are placed outboard of the pump and between the pump and turbine, the turbine is overhung and the shaft is typically sized based on critical speed considerations. If the bearings are both placed outboard, one at each end of the turbopump assembly, the shaft is typically sized based on the shear stress. With the latter configuration, the shaft can be reduced in diameter at the bearing journals since torque is transmitted only between the pump and turbine, and the DN limit can be ignored by inputting a large value. Hydrostatic bearings can also be modeled by inputting a large value, since these bearings are not DN-limited.

9 - Locations 23-24, Pump diameter ratio limit: The default value of 0.8 is the approximate upper limit on inlet/outlet diameter ratio for a centrifugal impeller. Values between 0.8 and 1.0 would indicate a mixed-flow design and an axial-flow design would have a value of 1.0.

10 - Locations 79-80, Minimum turbine admission fraction: This input depends on the turbine types selected (locations 100-101) and the following values are recommended:

Single Stage	.1
Two-row velocity compounded	.5
Two stage	.9

11 - Locations 81, 88, & 155, Coolant flow split: With the thrust chamber cooling data currently in the program, this value has no effect on the balance.

12 - Locations 94-95, Optimizer reflection factor and termination tolerance: These variables are described in the OPT subroutine description. Selection of the tolerance is discussed in the User Instructions section.

13 - Location 99, Turbine annulus area - speed squared limit: This limit is the product of the turbine blade annulus area and the square of the rotational speed and is a measure of the centrifugal stress. The allowable value depends on the blade configuration, materials, turbine inlet temperature, propellant combination, and life requirements.

14 - Location 129, Double-entry oxidizer pump flag: A double entry pump consists of two identical impellers mounted back to back with a common discharge volute in the center. Each impeller receives half the flow which allows higher speeds and smaller diameters for a given NPSH capability, or conversely, improved NPSH capability for a given diameter. Thrust balancing is also much easier with this design.

15 - Location 145, $Q_{NBL}/Q_{COMBUSTOR}$: This value is the fraction of the combustor coolant heat load that occurs prior to attachment of the boundary layer downstream of the injector. The boundary layer analyses used to predict losses in specific impulse account for the heat lost by the hot gas to the coolant after boundary layer attachment so the propellant enthalpy entering the chamber is increased by a like amount. The heat transfer prior to boundary layer attachment is ignored in calculating specific impulse but is used for calculating turbine inlet properties. Typical values for conventional chambers are in the range of .1 to .2.

16 - Locations 166 & 167, C* and kinetic efficiencies: Reliable estimates of C* and kinetic efficiencies may not always be available for cases of interest. For pump-fed systems, typical values are in the range of .97 - .997 for C* efficiency and .97 - 1.0 for kinetic efficiency. The higher values are associated with higher thrust levels and chamber pressures.

DIAGNOSTIC MESSAGES

Several routines provide diagnostic messages if numerical problems are encountered or if input values result in unreasonable calculated values. Most diagnostics are associated with optimization constraints, since initial guesses on optimizer independent variables are required which do not violate any of the implicit constraints. These messages are summarized below.

MAIN PROGRAM (AMAIN)

(1) "ERROR! TABLE SIZE XXXX .GT. 4010 RUN STOPS." This message indicates that the table containing theoretical performance data exceeds the dimension of the array holding the table. The array size is calculated from the values in the first line of the input file, which should be checked for accuracy and format. If the table does exceed 4010 values, the dimension must be increased.

(2) "FIRST GUESS CHECK: ERROR = XX." The first guess check option is a convenient way to assure that a case will run with a given set of initial guesses, especially if several cases are being run together. If "ERROR= 0" is printed, no implicit constraints were violated and the case should run. Otherwise, the number printed indicates the constraint that was violated.

SUBROUTINE CURVES

(1) "SIZE ENTRY. LE. ZERO. . ." The first entry in a table to be used by CURVES for interpolation must indicate the number of values of each independent variable.

(2) "THE FOLLOWING ______ VALUES ARE NOT MONOTONIC." The values of the independent variables in a CURVES array must be in order of increasing or decreasing magnitude.

SUBROUTINE EST

EST will print error messages and values of affected variables if convergence is not achieved in the specified number of interations or if a change in the independent variable does not affect the difference between the variables being converged. The program will normally recover and continue with subsequent iterations, in which case the message can be ignored. Otherwise, the program will probably terminate with a numerical error, some causes of which are discussed later in this section.

SUBROUTINE MAIND

(1) "BAD ALPHA . . . . CASE TERMINATED . . ." ALPHA is the optimizer reflection factor and must be greater than 1.0 (default = 1.3). If a bad value is input (location 94 in COMMON) the case will terminate.

(2) "ITERATION FAILURE, I(S) = XXX YYY." The specific impulse iteration in MAIND usually converges rapidly. If the required tolerance is not satisfied in 10 iterations, the program prints a message and the two most recently calculated values and continues calculation as if convergence had been achieved. Unless this occurs on the final balance and the difference is significant the message may be ignored.

(3) "OPTIMIZER ITERATION LIMIT EXCEEDED." The input limit on the number of optimizer iterations is designed to avoid excessive run times. If this limit is exceeded the current balance is printed and the case ends. The limit is applied to the total number of iterations and will not be the same as the value printed during program execution which includes only successful iterations, i.e., those not violating an implicit constraint.

(4) "X-ARRAY COMING OUT OF OPT." If an error "99" (see OPT musseages) is encountered MAIND prints the X-array which contains the optimizer complex values.

(5) "ERROR DETECTED NUMBER XX." If the initial guesses input to the program result in an implicit constraint violation, this message will appear with the number of the constraint. (See Implicit Constraints Heading) The appropriate optimizer variable must be changed and the case rerun. Occassionally this message will apear at the end of a run with an error number of 60. In this event the bypass flow should be checked; it will normally be slightly lower than the value specified in input location 5.

SUBROUTINE OPT

OPT prints the values of the independent variables and object functions every 10 iterations during program execution as well as error messages. The only error condition associated with OPT (error 99) is the detection of what appears to be a convex constraint or a non-simply-connected search field (see OPT subroutine description). This can occur due to iterations within the program which can result in slightly different values of some parameters when two balances are calculated with identical values (within machine accuracy) of the optimizer independent variables.

The optimizer first checks the initial guess to see that no implicit constraints are violated. It then fills the initial complex by filling in the initial guesses and replacing one value for each point with the upper or lower limit for one of the variables. If the new value results in a constraint violation, another point is tried halfway between the initial guess and the upper or lower limit. This process continues until a good point is found; if the interval-halving continues until the new point is back to the initial guess and a constraint violation is still indicated, the message "ERROR IN OPT" is printed along with values of KT, KK, V, and the Y-array. (KT is the number of successful iterations, KK is the complex point where the error occurred, V is the value of the object function for point KK, and Y contains the object function values for the entire complex). The error flag is set to -99 and control returns to MAIND.

After the initial complex is established the routine selects new points by projecting a line from the worst point through the centroid. Again, if a constraint violation occurs, the interval is halved, moving the new point toward the centroid. If the new point reaches the centroid and either a constraint is violated or the value of the object function is not an improvement over the worst point in the complex, the error flag is set to -99.

The normal response to an error 99 is to change one or more of the initial guesses since a slight change in the starting point will often eliminate this problem. Changes to chamber pressure, turbine pressure ratio, and pump speeds have proven most effective. The initial guesses should also be checked to be sure they are within the explicit limits. A value outside this range will be used on the first balance but will be changed thereafter, making it impossible to return to the starting point.

A related message may appear occasionally during termination checks. An RMS value of the complex points relative to the centroid requires that a balance be performed on the centroid values. If a constraint is violated, the message "OPT-CENTROID OUTSIDE CONSTRAINT = XX" is printed but no action is taken. If no further difficulties are encountered, the message can be ignored.

IMPLICIT CONSTRAINTS

The user will normally be concerned with the implicit constraint errors only during the check on initial guesses; the points tried and rejected by the optimizer for constraint violation will seldom be of interest. These constraints are listed by number in Table 8 and suggested corrective actions are included in Table 9 . The corrective actions should generally be tried in the order listed and occasionally two or more combined actions may be needed. Some corrections are not always practical, for example, changing chamber pressure is only appropriate when using the chamber pressure maximization option and the input value is the initial guess. Input locations corresponding to the corrective actions are indicated in Table 9.

MATHEMATICAL ERRORS

Some combinations of inputs may result in fatal mathematical errors, although the most likely occurrences have been eliminated by program changes when they first occurred. The following examples are given to provide the user with some insight as to the corrective actions that may be added.

Other than input errors, the most likely inputs to cause difficulty are the explicit constraints and, to a lesser degree, the initial guesses. For example, it is seldom desirable to limit the turbopump speeds or the maximum turbine pressure ratio (staged combustion or expander cycle), however, the input limits must be somewhat reasonable since they will be tried during establishment of the initial complex. A very high upper limit on turbine pressure ratio will result in a pump design with very high discharge pressure, leading to low efficiencies and excessive horsepower requirements. The resulting propellant heating in the pump may produce enthalpy levels which exceed the range of turbine drive gas property tables and may result in negative values for turbine gas properties. Similarly, if a staged-combustion-type lower limit on pressure ratio is used for a gas generator cycle, the turbine flowrate may exceed the initially estimated engine flowrate and lead to negative flowrates in the main chamber.

TABLE 8

IMPLICIT CONSTRAINT DIAGNOSTIC NUMBER

Number	Constraint
1	Main fuel pump impeller tip width minimum
2	Main oxidizer pump impeller tip width minimum
3	Main fuel pump inducer diameter minimum
4	Main oxidizer pump inducer diameter minimum
5	Main fuel turbopump bearing DN maximum
6	Main oxidizer turbopump bearing DN maximum
7	Main fuel pump inlet/exit diameter ratio maximum
8	Main oxidizer pump inlet/exit diameter ratio maximum
9	Main fuel pump impeller tip speed maximum
10	Main oxidizer pump impeller tip speed maximum
11	Main fuel pump inducer tip speed maximum
12	Main oxidizer pump inducer tip speed maximum
13	Main fuel pump discharge pressure maximum
14	NCU*
15	Main fuel pump impeller stage specific speed minimum
16	Main oxidizer pump impeller stage specific speed minimum
17	Main fuel pump impeller stage specific speed maximum
18	Main oxidizer pump impeller stage specific speed maximum
19	Main fuel pump impeller tip diameter minimum
20	Main oxidizer pump impeller tip diameter minimum
21	Main fuel pump impeller tip diameter maximum
22	Main oxidizer pump impeller tip diamter maximum
23	NCU
24	NCU
25	NCU
26	NCU
27	Oxidizer pump required NPSH too high
28	Fuel pump required NPSH too high
29	NCU
30	NCU
31	Main fuel pump speed reduced by turbine routine

* NCU - not currently used

TABLE 8 (Cont'd)

Number	Constraint
32	Main oxidizer pump speed reduced by turbine routine
33	Main fuel turbine admission reduced
34	Main oxidizer turbine admission reduced
35	Oxidizer pump speed reduced by pump routine
36	Fuel pump speed reduced by pump routine
37	NCU
38	NCU
39	NCU
40	Fuel kick pump tip width minimum
41	Fuel kick pump inlet/exit diameter ratio maximum
42	Fuel kick pump specific speed maximum
43	Fuel kick pump tip diameter minimum
44	Main oxidizer turbine iterations exceeded
45	Main fuel turbine iterations exceeded
46	Oxidizer pump iterations exceeded
47	Fuel pump iterations exceeded
48	Nozzle bulk coolant temperature exceeded
49	Combustor bulk coolant temperature exceeded
50	Oxidizer kick pump tip width minimum
51	Oxidizer kick pump inlet/exit diameter ratio maximum
52	Oxidizer kick pump specific speed maximum
53	Oxidizer kick pump tip diameter minimum
54	NCU
55	Oxidizer main turbine hub/tip minimum violated
56	Fuel main turbine hub/tip minimum violated
57	NCU
58	NCU
59	GG Pc too high
60	Main turbine flowrate > available

Implicit Constraint Diagnostic Cures

Diagnostic	Cure (Input Locations)
1-2 Main Pump Impeller Tip Width Minimums	a) Increase main pump speed (151-152)
	b) Reduce turbine pressure ratios (156)
	c) Reduce chamber pressure (3)
	d) Reduce system Delta-P's (131-136, 187-188)
	e) Increase number of centrifugal stages (117-118)
3-4 Main Pump Inducer Diameter Minimums	a) Reduce main pump speed (151-152)
	b) Increase inducer hub/tip ratio (125-126)
	c) Reduce NPSH (113-114)
	d) Reduce engine inlet pressure (111-112)
5-6 Main Pump Bearing DN Maximums	a) Reduce main pump speed (151-152)
	b) Reduce turbine pressure ratios (156)
	c) Reduce chamber pressure (3)
	d) Reduce system Delta-P's (131-136, 187-188)
7-8 Main Pump Inlet/Exit Diameter Ratio Maximums	a) Reduce main pump speed (151-152)
	b) Increase turbine pressure ratios (156)
	c) Increase chamber pressure (3)
	d) Increase system Delta-P's (131-136, 187-188)
	e) Reduce number of centrifugal stages (117-118)
9-10 Main Pump Impeller Tip Speed Maximums	a) Reduce turbine pressure ratios (156)
	b) Reduce chamber pressure (3)
	c) Reduce system Delta-P's (131-136, 187-188)
	d) Reduce main pump speed (151-152)
	e) Increase number of centrifugal stages (117-118)

Diagnostic		Cure (Input Locations)
11-12	Main Pump Inducer Tip Speed Maximums	a) Reduce main pump speed (151-152) b) Reduce inducer inlet hub/tip ratio (125-126)
13	Main Fuel Pump Discharge Pressure Maximum	a) Reduce chamber pressure (3) b) Reduce turbine pressure ratios (156) c) Reduce system Delta-P's (131-136, 187-188)
14	Not Currently Used	
15-16	Main Pump Impeller Specific Speed Minimums	a) Increase main pump speed (151-152) b) Reduce turbine pressure ratios (156) c) Reduce chamber pressure (3) d) Reduce system delta-P's (131-136, 187-188) e) Increase number of centrifugal stages (117-118)
17-18	Main Pump Impeller Specific Speed Maximums	a) Reduce main pump speed (151-152) b) Increase turbine pressure ratios (156) c) Increase chamber pressure (3) d) Increase system Delta-P's (131-136, 187-188) e) Reduce number of centrifugal stages (117-118)
19-20	Main Pump Impeller Tip Diameter Minimums	a) Reduce main pump speed (151-152) b) Increase turbine pressure ratios (156) c) Increase chamber pressure (3) d) Increase system Delta-P's (131-136, 187-188) e) Reduce number of centrifugal stages (117-118)
21-22	Main Pump Impeller Tip Diameter Maximums	a) Increase main pump speed (151-152) b) Reduce turbine pressure ratios (156) c) Reduce chamber pressure (3) d) Reduce system Delta-P's (131-136, 187-188) e) Increase number of centrifugal stages (117-118)

Diagnostic		Cure (Input Locations)
23-26	Not Currently Used	
27-28	Required NPSH Too High	a) Reduce main pump speed (151-152) b) Increase engine inlet NPSH (113-114)
29-30	Not Currently Used	
31-32	Main Pump Speeds Reduced by Turbine Routines	a) Reduce main pump speed (151-152) b) Increase main turbine pressure ratios (156)
33-34	Main Turbine Admissions Reduced	a) Reduce main turbine admissions (153-154) b) Reduce main turbine pressure ratios (156)
35-36	Main Pump Speeds Reduced by Pump Routines	a) Reduce main pump speed (151-152) b) Reduce turbine pressure ratios (156) c) Reduce chamber pressure (3) d) Reduce system Delta-P's (131-136, 187-188)
37-39	Not Currently Used	
40	Fuel Kick Pump Tip Width Minimum	a) Increase main pump speed (151) b) Reduce turbine pressure ratios (156) c) Reduce system Delta-P's (131-136, 187-188)
41	Fuel Kick Pump Inlet/Exit Diameter Maximum	a) Reduce main pump speed (151) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136, 187-188)
42	Fuel Kick Pump Specific Speed Maximum	a) Reduce main pump speed (151) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136, 187-188)
43	Fuel Kick Pump Tip Diameter Minimum	a) Reduce main pump speed (151) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136, 187-188)

Diagnostic		Cure (Input Locations)
44-45	Main Turbine Iterations Exceeded	a) Increase turbine pressure ratios (156)
46-47	Main Pump Iterations Exceeded	a) Change pump speed initial guesses (151-152)
48	Nozzle Bulk Coolant Temperature Exceeded	a) Reduce combustor coolant/total fuel flow ratio (155) b) Reduce chamber pressure (3) c) Reduce chamber mixture ratio (4) d) Reduce nozzle area ratio (2)
49	Combustor Bulk Coolant Temperature Exceeded	a) Increase combustor coolant/total fuel flow ratio (155) b) Reduce chamber pressure (3) c) Reduce chamber mixture ratio (4)
50	Oxidizer Kick Pump Tip Width Minimum	a) Increase main pump speed (152) b) Reduce turbine pressure ratios (156) c) Reduce system Delta-P's (131-136)
51	Oxidizer Kick Pump Inlet/Exit Diameter Ratio Maximum	a) Reduce main pump speed (152) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136)
52	Oxidizer Kick Pump Specific Speed Maximum	a) Reduce main pump speed (152) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136)
53	Oxidizer Kick Pump Tip Diameter Minimum	a) Reduce main pump speed (152) b) Increase turbine pressure ratios (156) c) Increase system Delta-P's (131-136)
54	Not Currently Used	
55-56	Main Turbine Hub/Tip Minimums	a) Reduce main pump speeds (151-152) b) Increase main turbine admissions (153-154)

Diagnostic		Cure (Input Locations)
57-58	Not Currently Used	
59	Gas Generator Chamber Pressure too High	a) Reduce turbine pressure ratios (156) b) Reduce turbine discharge pressures (140)
60	Main Turbine Flow Rate > Available	a) Increase turbine pressure ratios (156) b) Reduce chamber pressure (3) c) Reduce turbine bypass (5) d) Reduce system Delta-P's (131-136, 187-188)